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NOVEMBER-DECEMBER 1941

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PATTERN OF GROUND-WATER FLOW AND SOLUTION

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ABSTRACT

The intensive geologic investigations during the past few years in connection with the design and construction of dams and other engineering works have established the common existence of deep bedrock solution, which has occurred well below the water table. Although this deep flow and solution are entirely harmonious with hydraulic principles, an important aspect of the problem of the optimum depth of ground-water flow and solution is the matter of *adjustment* of the subsurface circulation. As this adjustment becomes more perfect, deep flow and solution progressively diminish and flow and solution in the upper levels of the zone of saturation increase correspondingly. In the latter stages of the cycle, cave formation probably occurs at higher levels by the concentration of lateral flow through high-level master-conduits. In the earlier stages, flow is not concentrated but is distributed throughout the entire vertical section, oriented along arcuate paths which descend deeply before recurving upward to the point of discharge.

INTRODUCTION

Solution by ground water involves two separate considerations: (1) the mechanism of ground-water circulation and (2) the solutional effects of this circulation. Because solution progressively alters the underground conduits of flow, causing changes in the mechanism and pattern of circulation, new conditions arise in continuous sequence, and theoretical motivations for the flow of ground water under given conditions therefore apply only transitorily.

Adjustment, used here with the implication that it is an end-state, is in reality never fully realized; final adjustment of underground flow and solution can be achieved only under conditions of static landscape, devoid of hydraulic gradient. This condition would be most closely approximated under conditions of complete peneplanation. Wherever topographic diversity exists, there must occur a sequence of landscape changes with which the pattern of ground-water flow will maintain a shifting, approximate relationship. However, in this pursuit of conformity to changing topographic conditions, the pattern of ground-water circulation can never achieve more than an asymptotic approximation of complete adjustment.

Varying approximations of adjustment are most important factors in the solutional activity of ground water. The fundamental difference between diverse manifestations of underground solution in homogeneous rocks is in many instances a matter of differing degree of hydrologic adjustment to varying topographies. The controversy concerning the optimum depth of formation of limestone caves may primarily result from differing concepts of what constitutes hydrologic adjustment to a given topography. W. M. Davis[1] postulated the formation of limestone caves at depth by deep flow of ground water, while A. C. Swinnerton[2] advocated cave formation chiefly at shallow depths by lateral flow near the water table. The deep underground flow postulated by Davis is strictly compatible with hydraulic theory; there can be no doubt that it occurs very generally. However, Swinnerton advanced compelling arguments that many, if not most, caves have been formed at shallow depths. A reconciliation of the two views is possible on the assumption that the deep flow of Davis, probably capable of cave formation under certain conditions, diminishes in importance as an agent of solution as hydrologic adjustment of an area progresses, shallow ground-water flow becoming increasingly important as the degree of hydraulic adjustment increases and operating more effectively toward cave formation in all but the initial, unadjusted stages of the hydrologic cycle.

Although the development of hydrologic adjustment to an evolv-

[1] "Origin of Limestone Caverns," *Bull. Geol. Soc. Amer.*, Vol. XLI (1931), pp. 475–628.

[2] "Origin of Limestone Caverns," *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), pp. 663–94.

ing topography involves variables which make its elucidation very difficult, the general pattern and mechanism of ground-water circulation under theoretically ideal conditions can be analyzed more precisely. It is the purpose of this paper (1) to apply the principles of hydraulic analysis to the problem of ground-water flow and thus to determine the character of initial circulation before adjustment begins; (2) to consider the directions normally taken by the adjusting processes which progressively alter the original pattern of flow; and (3) to predict the relationship between this flow and the solution it accomplishes and the trends which the solutional effects of these adjusting processes may be expected to follow.

THEORETICAL PATHS OF GROUND-WATER FLOW

For two-dimensional flow, the general differential equation for the steady flow of water through isotropic materials has the form of a Laplace equation

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0. \tag{1}$$

It is obtained by substituting Darcy's law of flow

$$u = k\frac{dh}{dx}; \; v = k\frac{dh}{dy} \tag{2}$$

into the equation of continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0. \tag{3}$$

This equation presupposes the following conditions: (1) the voids are completely filled with water; (2) no change in the size of the voids occurs; (3) the quantity of flow entering into any small element of volume is equal to the quantity flowing out of this element of volume during any given time; and (4) the water and the material are incompressible.

Equation (1) represents two families of curves intersecting at right angles which are usually referred to as the flow lines and equipotential lines (lines of equal or relative head loss). A graphical solution for practically all two-dimensional seepage problems can be

made by drawing lines representing these two families of curves. In Figure 1 a few flow lines are selected which are so related that the same fraction ΔQ of the total seepage is passing between any pair of adjoining flow lines, and a few corresponding potential lines are selected, drawn so that the fractional drop of the total head between any pair of adjoining potential lines is constant throughout. Where the head causing flow is constant, these two sets of curves will intersect to form a series of squares.

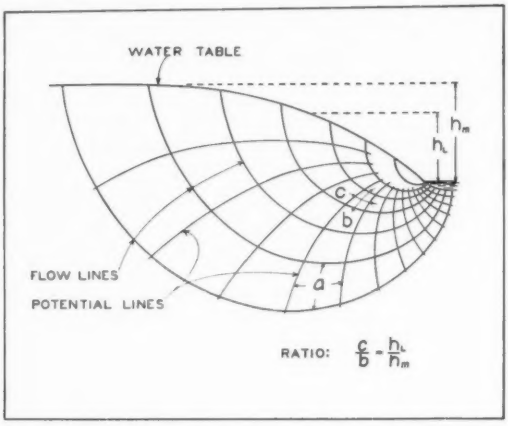

FIG. 1.—Construction of flow net showing flow lines and potential lines and their interrelation under conditions of variable head.

However, in a problem where the elevation of free water surface and, consequently, the head causing flow vary with the distance from the point of discharge, the graphical solution by squares must be modified in accordance with these varying heads. The increasing head approaches a constant maximum value away from the discharge pool, and the flow lines influenced by constant head will intersect the potential lines to form squares. But, with the reduced heads nearer the river, these intercepted quadrangles will become rectangles, with the ratio of the lengths of their sides varying as the ratio of the average head causing flow through that channel to the maximum head. The difference between these lengths will become progressively

greater as the head becomes smaller (the rectangles become more elongated). The drop in the head between any two adjoining potential lines is a constant fraction of the head causing flow at any point, but the actual amount of drop in head between any two potential lines varies as the head causing flow, being smaller under the lower heads.

The flow pattern is drawn by balancing the positions of these various lines against each other so that the above conditions may be fulfilled in accordance with the governing equations (Fig. 1).

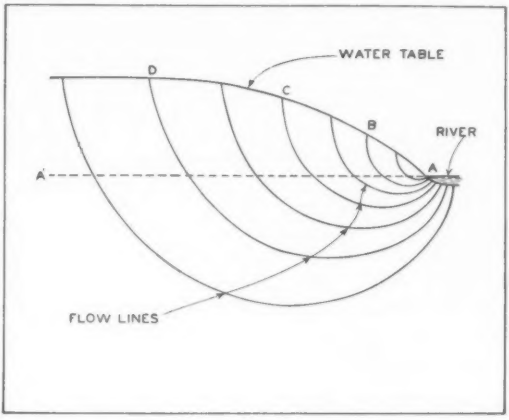

FIG. 2.—Configuration of lines of flow through a homogeneous permeable material.

Figure 2 is a graphic representation of lines of flow through a homogeneous medium, from a free water surface to a point of discharge, drawn as in Figure 1, but with the potential lines omitted for simplicity. The line *ABCD* represents a free water table with discharge in a river of which point *A* is one bank. The position of the water table is assumed to be constant (discharge equals recharge).

Laminar flow affects all the water down to the bottom of the section; the flow is not limited to the zone lying above the horizontal plane at the point of discharge elevation (*A*–*A'*, Fig. 2).

The following generalizations concerning laminar flow under these ideal conditions—through a homogeneous medium from an elevated

water surface to a lower point of discharge—follow from a critical examination of Figure 2.

1. By construction, the quantities of flow between all pairs of adjacent lines are equal. Since, however, the area between any two adjacent flow lines varies, diminishing progressively from the point of entrance (water-table surface) to the point of discharge, the velocity of flow between any two flow lines progressively increases in the same direction. The rate of this increase of velocity is greater along the shorter paths because the areas diminish more rapidly between the shorter paths than do those between longer paths.

2. Along each path between adjacent flow lines, the initial velocity of water as it starts its passage from the water-table surface to the point of discharge (herein called the "entrance velocity") bears a direct relation to the slope of the water table, which determines the length of any path and the head applying to it. Along a water table of constant slope, the entrance velocities for all paths would be constant because these flow lines form a family of curves whose lengths are proportional to the slope distances from the discharge point, and hence to the head causing flow. With nonuniform water-table slopes which are more usual in nature, as drawn in Figure 2, the entrance velocities along the slope are reduced with increase in distance from the point of discharge.

3. Flow lines from a theoretical water table of constant slope would be equally spaced at their points of origin on the water-table surface. With a water table of varying slope, the spacing of the paths of flow varies, being more widely spaced in the regions of flatter water-table slopes progressively more remote from the point of discharge.

4. It is self-evident that the lengths of the paths of travel (flow lines) increase with increasing distance from the point of discharge—that is, not only is the straight-line distance progressively greater, but the paths become successively more arcuate and therefore less direct. The time required for the passage of water from successively more remote points of origin to the point of discharge is increased, first, because of the increasing lengths of paths, and second, because of the decreasing rates of increase of velocity along these successively longer paths.

It is pertinent to the discussion which follows to note that subsequent adjustment of the pattern of underground drainage lines by selective solutional enlargement will lead to the destruction of the initial homogeneity of the rock and to the abandonment of the initial arcuate paths in a manner promoting concentration of flow through master-conduits of secondary origin which permit direct lateral flow.

COMPARABILITY OF FLOW THROUGH LIMESTONE

In order to apply the preceding analysis of flow to limestone terrains, it is necessary to assume that secondary openings occur more or less uniformly throughout the rock mass in intersecting systems. Most limestones are jointed in a manner roughly fulfilling these requirements. If joints or other openings do exist and are sufficiently open for the transmission of ground water, the flow will pass from joint to joint in the closest approximation to the ideal arcuate path which the configuration of the joint system will permit.

Because the spacing, open character, size, distribution, and intersection of the joints depart from uniformity throughout the rock, the analogy between natural flow through rocks and flow through an ideal homogeneous medium departs from perfection to a variable but significant degree.[3]

RELATION OF IDEAL PATTERN OF GROUND-WATER CIRCULATION TO BEDROCK SOLUTION

In rock of uniform solubility the amount of solution accomplished by a given pattern and volume of ground-water circulation will depend upon several factors, perhaps the most important being the concentration of carbon dioxide. To avoid overvoluminous discussion and to emphasize the fundamental relationships involved, it will be assumed that equal flows through equal volumes of rock accomplish equal amounts of solution along all paths of flow. More precise analyses, taking cognizance of possible different carbon dioxide concentrations and other pertinent variables, do not mitigate the general conclusions which follow but in most cases accentuate the trends which are noted.

The flow lines in Figure 2 are so drawn that equal quantities of

[3] Heterogeneous lithology or geologic structure, or pre-existing master-conduits of flow—as along fault planes—represent special conditions to which these general arguments are not meant to apply.

water pass between any two adjacent lines in a unit of time. However, as shown in section in Figure 2, the volumes of rock between any two paths of flow are different, smaller volumes existing between the more closely spaced paths originating near the point of discharge which only traverse zones of higher elevation. The same amount of solution therefore occurs between each pair of flow paths, but larger volumes of rock are involved between flow lines which originate at points remote from the river and smaller volumes between successive pairs of flow lines originating at points closer to the river. The least

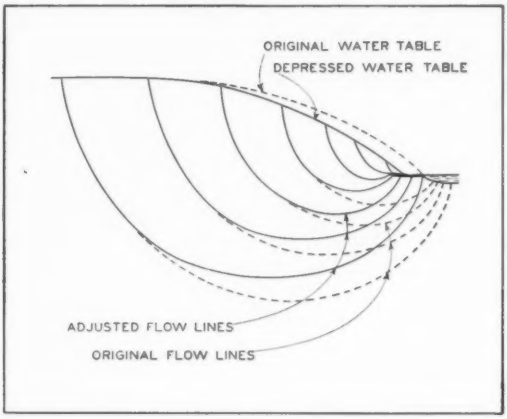

FIG. 3.—Early development of a master-conduit and corresponding adjustment of lines of flow.

volume of rock occurs between the shallowest paths which are also closest to the river. It follows that each of the successively smaller volumes of rock occurring between the shorter and shallower paths near the river will be dissolved to a relatively greater degree. That is, a unit volume of rock in a zone traversed by the shorter and shallower paths of flow experiences more solution than the same volume affected by the longer and deeper paths of flow.

This relative concentration of solution along the shorter paths will lead to the development of conduits having larger diameters, and more direct connection with the point of discharge, in the upper levels of the rock (at shallow depths below the water table). These

high-level solution channels will develop into master-conduits by coalition of adjacent channels, with the inevitable consequence of concentrated and more voluminous flow, which will lead to lowering of the water table in the immediate vicinity.

Figure 3 indicates an early stage of this coalition of cavities into such a master-conduit and the consequent lowering of the water table. The hydraulic-head relations have been altered and the master-conduit has become the discharge zone for the lines of flow. The flow lines have been drawn to harmonize with these new condi-

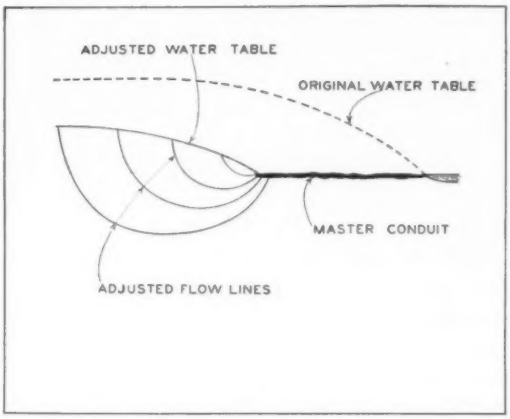

FIG. 4.—Later development of a master-conduit and corresponding adjustment of lines of flow.

tions. The paths of flow have altered in shape—especially in regions near the point of discharge (compare with Fig. 2)—but the depth of flow at points remote from the depressed portion of the water table are relatively unaffected.

Figure 4 indicates a more advanced stage of master-channel development. The master-conduit has been enlarged and extended laterally and has become the point of discharge. The water table has been lowered to the level of the master-conduit. Rearrangement of flow lines has greatly decreased the deep circulation, increasing quantities of flow being diverted into the master-conduit where lateral flow predominates. The master-conduits would be only partially or periodically submerged at this stage.

At localities more remote from the point of discharge, the level of the water table may be relatively unaffected and deep flow may continue in these regions for an additional period of time. The augmentation of superficial (lateral) flow, with an associated diminution of deep flow, therefore operates first in close proximity to the point of discharge and advances progressively toward the highlands.

CONCLUSIONS

Initial flow through homogeneous soluble materials from an elevated water surface to a lower point of discharge will take place along curved paths which descend below the point of discharge before recurving upward toward their points of emergence.

Solution will normally occur along all paths but will be initially more effective along the shorter paths traversing the upper portions of the zone of saturation.

Continued solution lowers the water table and leads to progressive concentration of flow and solution at the higher levels and to a diminution of flow and solution at greater depths.

The postulated conditions of homogeneity upon which the foregoing analysis is based are not encountered in limestone terrains where flow occurs exclusively through secondary openings. However, limestones possessing intersecting joint patterns of more or less uniform distribution may approach the postulated homogeneity to the degree that similar principles govern the mechanism of underground flow. To the extent that this is true, the observable widespread occurrence of deep zones of bedrock solution are entirely compatible with the probability that the most extreme manifestations of solution occur at shallower depths in the upper parts of the zone of saturation.

The initial flow, occurring both at great and at shallow depths, causes solution which is quantitatively most pronounced in the upper zones. Progressive concentration of solution in the upper part of the zone of saturation produces master-conduits and causes the eventual diminution of flow and solution at deeper levels.

The concentration of flow in high-level conduits occurs first near the initial point of discharge but advances progressively toward the highlands (toward the water-table divide) as the master-conduits progressively enlarge and elongate in a headward direction.

RELATION OF THE YAKIMA BASALT TO THE KEECHELUS ANDESITIC SERIES[1]

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ABSTRACT

The Yakima basalt of eastern Washington is associated toward the west in the Cascade Mountains with the Keechelus andesitic series. The latter series has generally been regarded as the younger.

In the Mount Aix quadrangle the upper part of the Keechelus andesitic series is mapped as a separate unit—the Fifes Peak andesite. Marginal flows of the Yakima basalt overlap the Fifes Peak andesite and are clearly younger than the andesite.

The Yakima basalt is generally regarded as Middle Miocene but may be Upper Miocene. The Fifes Peak andesite is presumably not younger than Middle Miocene. The lower part of the Keechelus andesitic series may be no younger than Oligocene. The Snoqualmie granodiorite is probably intermediate in age between the lower part of the Keechelus andesitic series and the Fifes Peak andesite.

The Cascade Mountains of southern Washington owe their present height principally to uplift rather than to the accumulation of volcanic materials.

INTRODUCTION

The Columbia River lava is well known as one of the largest exposures of the "plateau basalts." Its form is that of an enormous composite lens of basaltic flows associated with minor amounts of sediments and pyroclastic materials, and it covers most of southeastern Washington as well as northeastern Oregon and adjacent parts of Idaho. In parts of southeastern Washington the lava is almost certainly more than 4,000 feet thick and possibly more than 5,000 feet thick. Both the number of flows and the total thickness diminish as the margin of the lens is approached, and from these relations it appears that the flows filled a basin in the older rocks to a nearly uniform level. Where the edge of this composite lens has been eroded, a reasonable approximation of the original boundary of the lava field may be obtained by projecting the upper surface of the lavas toward the margin of the basin until the projected surface intersects the land surface that antedates the lavas.

It may be presumed on the basis outlined that the lava never extended far north of Spokane River in northeastern Washington.

[1] Published by permission of the director of the Geological Survey, U.S. Department of the Interior. This paper presented under a slightly different title at the June, 1940, joint meeting of the American Association for the Advancement of Science and the Geological Society of America in Seattle.

From the confluence of that stream with the Columbia River, the original boundary followed approximately the present course of the Columbia River westward to the vicinity of Wenatchee and thence southwesterly to the Mount Stuart quadrangle (see Fig. 1). George Otis Smith traced the boundary of the lava southwestward across the Mount Stuart quadrangle into the southeastern corner of the Snoqualmie quadrangle and proposed the name "Yakima basalt"[2] for the main portion of this lava, the age of which he determined to

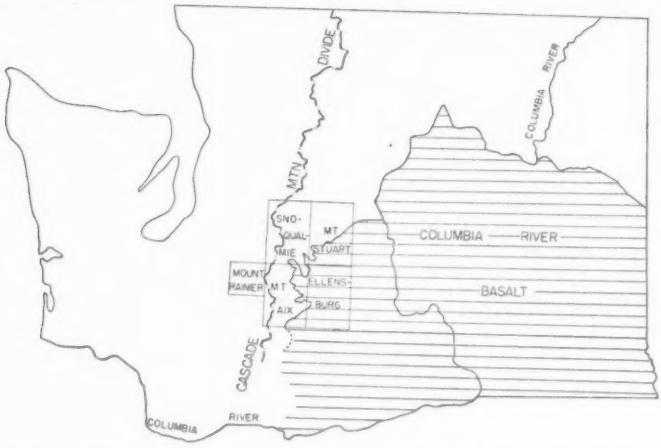

FIG. 1.—Index map of Washington showing location of the Mount Aix, Snoqualmie, Mount Stuart, and Ellensburg quadrangles, and the Mount Rainier special sheet, with their positions relative to the margin of the Columbia River basalt and the Cascade Mountain divide.

be Miocene. The Geological Survey has sanctioned Smith's usage of the name "Yakima basalt," while retaining the term "Columbia River lava" (or basalt) for use in the original broad sense; but others have restricted the name "Columbia River basalt" to the Miocene portion, so that the two names today are used more or less interchangeably.[3]

In the Snoqualmie quadrangle (see Fig. 2), G. O. Smith and F. C.

[2] "Geology and Water Resources of a Portion of Yakima County, Washington," *U.S. Geol. Surv. Water Supply Paper 55* (1901), pp. 15–17.

[3] M. Grace Wilmarth, "Lexicon of Geologic Names of the United States (including Alaska)," *U.S. Geol. Surv. Bull. 895* (1938), pp. 494–95.

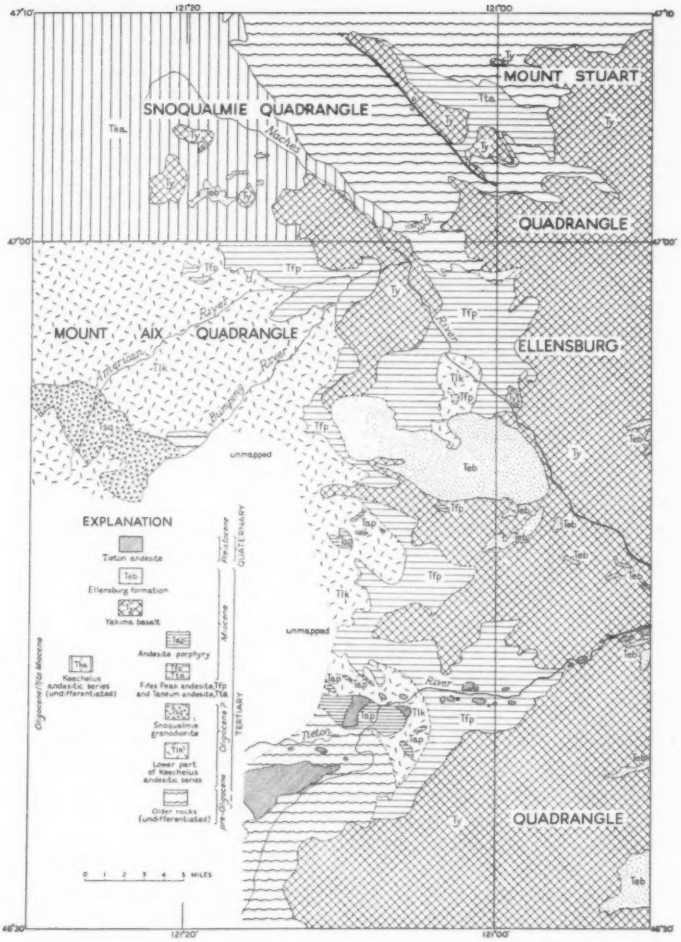

FIG. 2.—Areal geology of part of the Mount Aix quadrangle, and adjoining portions of the Snoqualmie, Mount Stuart, and Ellensburg quadrangles, Washington. Geology of the Mount Aix quadrangle mapped by W. C. Warren in 1932, 1935, and 1936. Geology of the adjoining quadrangles slightly modified from folios 86, 106, and 139 of the U.S. Geological Survey.

Calkins found another vast assemblage of volcanic rocks covering much of the western half of that quadrangle and extending far to the north, west, and south. For this group of volcanic rocks they proposed the name "Keechelus andesitic series,"[4] denoting not only that these rocks are mainly andesitic but also that rocks of more than one age are included. In their text they divide the Keechelus into an older and a younger group "locally separable on lithologic grounds (supported by structural and topographic data)." The older portion was assigned to the Miocene, while it was thought that the younger portion might be Pliocene or younger.

In the Snoqualmie quadrangle, the line of contact between the Yakima basalt and the Keechelus andesitic series is confined to a small area in the synclinal valley of Naches River in the southeastern corner of the quadrangle. Study of these limited and rather poor exposures led Smith and Calkins to believe that the Keechelus andesitic series was younger than the Yakima basalt. From this modest beginning a robust concept has developed in the minds of some workers that the growth of the Cascade Mountains in this region has been caused by the accumulation of volcanic materials subsequent to the extrusion of the Yakima basalt, in a manner analogous to that which is generally postulated for the same range in Oregon.

During the course of my study[5] in the Mount Aix quadrangle (see Fig. 1), the division of the Keechelus andesitic series as suggested by Smith and Calkins[6] was found to be practicable, but the Yakima basalt was found to be younger than the Keechelus andesitic series rather than older. This discovery requires not only a reconsideration of age relations but also some revision of concepts on the structure of the Cascade Mountains in this region.

Because of other commitments, my field work on this project has not been carried so far as was originally planned; nevertheless, some results of this study are here placed at the disposal of other workers in this fascinating area.

[4] "Description of the Snoqualmie Quadrangle," *U.S. Geol. Surv. Folio 139* (1906), pp. 8–9.

[5] Six weeks in 1932, four months in 1935, and two weeks in 1936 were spent mapping the geology, using the Geological Survey topographic map of the Mount Aix quadrangle as a base.

[6] *Op. cit.*, p. 8.

STRATIGRAPHY

In the Mount Aix quadrangle the Keechelus andesitic series has been divided into two units. For the younger part, considered to be a lithologic and stratigraphic unit, the name "Fifes Peak andesite" is proposed. Possibly the lower part of the Keechelus andesitic series can be further subdivided, and in any case the present studies of it are too incomplete to burden it with a new name, so that in the present discussion it will be referred to simply as the lower part of the Keechelus.

LOWER PART OF THE KEECHELUS

The lower Keechelus consists of a heterogeneous group of felsitic to basaltic rocks, including flows, dike rocks, breccias, agglomerates, and tuffs, as well as minor amounts of sediments. Dacites, which were thought to be andesites in the field, predominate over minor amounts of basaltic, rhyolitic, and sedimentary rocks. The lower Keechelus rocks are characteristically altered, and the dacites and basalts typically have a greenish tone, owing to the presence of numerous secondary iron-rich minerals.

The structure of the lower Keechelus rocks is complex and needs further study. In general, the folds trend northwestward; some of the dips are as high as 60°, but 30°–40° dips are more prevalent. Many of the dips were read on water-laid tuffs which were not likely to have high initial dips, such as characterize the Fifes Peak andesite in many places.

In the center of the Mount Aix quadrangle, the lower Keechelus surrounds a core of older rocks which will require much additional study. On Bumping River the lower Keechelus lies unconformably on an arkose probably belonging to the Eocene continental deposits of this region. On Tieton River intrusive rocks younger than the lower Keechelus separate it from a highly deformed group of graywackes and greenstones invaded by granitic rock.

In the northwestern part of the Mount Aix quadrangle, the lower part of the Keechelus has been invaded by quartz diorite. This intrusive rock extends into Mount Rainier National Park, where it has been described and correlated[7] with the Snoqualmie granodiorite of

[7] H. A. Coombs, "The Geology of Mount Rainier National Park," *Washington Univ. Publ. in Geology*, Vol. III, No. 2 (1936), pp. 167–70.

the Snoqualmie quadrangle.[8] Widespread metamorphism by magmas related to the Snoqualmie granodiorite may have been responsible for the greenish tone of the lower Keechelus rocks.

G. E. Goodspeed and H. A. Coombs[9] have recently presented evidence that certain breccias in the lower part of the Keechelus have been developed by metasomatic alteration of sedimentary rocks. Some of the lower Keechelus rocks in the northwestern part of the Mount Aix quadrangle may also be best explained in this manner. These pseudo-volcanic materials are seldom far from exposures of plutonics. However, the greater part of the rocks mapped as lower Keechelus in this quadrangle have the appearance, in the field and under the microscope, of normal flows and pyroclastic materials.

Along most of its eastern border the lower Keechelus is overlain unconformably by the Fifes Peak andesite.

FIFES PEAK ANDESITE

This group of flows, agglomerates, and tuffs occupies a narrow strip along the eastern side of the Mount Aix quadrangle (see Fig. 2). The proportion of flows to agglomerates and tuffs varies greatly from place to place; on the whole, the pyroclastic materials undoubtedly have the greater volume. The flows are black on fresh exposures and are dense to vitreous, porphyritic rocks with clear phenocrysts of plagioclase. On weathered surfaces the rock is brownish with chalky white phenocrysts. The tuffs are yellow to buff and show little variation. The agglomerates are extremely variable in color, with grays, reds, and purples predominating.

Microscopically, both the flows and the agglomerates are surprisingly uniform in their mineral content. Phenocrysts of plagioclase, hypersthene, augite, and magnetite occur in a glassy to holocrystalline groundmass with a second generation of plagioclase and pyroxene. The plagioclase phenocrysts are highly zoned, varying in composition from $Ab_{35}An_{65}$ in the center to $Ab_{55}An_{4}$ in the rim. They contain numerous inclusions of magnetite and pyroxene, which are usually confined to an intermediate zone, with both the center and the rim of the phenocryst free of inclusions. The pyroxene pheno-

[8] Smith and Calkins, *op. cit.*, pp. 9–10.

[9] "Replacement Breccias of the Lower Keechelus," *Amer. Jour. Sci.*, Vol. XXXIV (5th ser., 1937), pp. 12–23.

crysts are commonly altered to a brownish isotropic substance, although the remainder of the rock is usually fresh. The plagioclase of the groundmass is calcic andesine.

The Fifes Peak andesite has been extruded from a number of vents, some of which are still recognizable, although greatly dissected. The most prominent of these is Fifes Peak, in the northern part of the quadrangle. A low dome of lower Keechelus rocks surrounded by outward-dipping Fifes Peak andesite, on Naches River near the east edge of the quadrangle, is believed to represent the site of a volcano which has since been thoroughly eroded. The structure of the volcanic materials on Tieton River near the east edge of the quadrangle also appears to indicate proximity to two or more vents in that area.

Dips in the Fifes Peak andesite are extremely variable and are probably in large part initial, as indicated by the relation of the dips to the vents. But in the northeastern part of the quadrangle, where flows are most abundant and the structure appears most reliable, the rocks have a general northeasterly dip, which steepens in the vicinity of Naches River and then reverses to form a syncline along the river.

The Fifes Peak andesite thins and thickens abruptly within short distances as a consequence of its mode of extrusion from more than one vent. On Tieton River a vertical thickness of about 2,700 feet is exposed, while a few miles to the south the andesite disappears entirely.

Smith and Calkins,[10] as well as Coombs,[11] have indicated the unconformable relation between the upper Keechelus (Fifes Peak andesite) and the lower Keechelus in the areas studied by them. In the Mount Aix quadrangle the unconformity is suggested by the generally steeper dips of the lower Keechelus rocks and by their notably greater metamorphism. Truncation of the lower Keechelus prior to the Fifes Peak volcanism seems probable, as the contact between the two shows little relation to the structure of the older formation.

The Fifes Peak andesite has not been found in contact with the Snoqualmie granodiorite, but a clue to their relative ages is afforded

[10] *Op. cit.*, p. 8.

[11] "The Geology of Mount Rainier National Park," *Washington Univ. Publ. in Geol.*, Vol. III, No. 2 (1936), pp. 164–67.

by the difference in metamorphism between the Fifes Peak andesite and the lower Keechelus rocks. If the alteration of the latter is due to the intrusion of the grandiorite, the lack of such alteration in the Fifes Peak andesite suggests that it is younger than the granodiorite.

ANDESITE PORPHYRY

A number of small intrusive masses crop out within the boundaries of the lower part of the Keechelus. These bodies range from small dikes to masses one or two miles in diameter. The texture of the rock varies with the size of the body, from fine-grained to coarsely porphyritic. Megascopically, the coarsest porphyry resembles a plutonic rock, but under the microscope its porphyritic character is obvious, and it appears very unlike the Snoqualmie granodiorite.

The mineralogy of these porphyries is very similar to that of the Fifes Peak andesite, and the porphyries probably represent a hypabyssal phase of the same volcanism. It is interesting to note that these bodies lie along the projected trend of very similar porphyries in Oregon, as mapped and described by A. F. Buddington and Eugene Callaghan.[12]

YAKIMA BASALT

The Yakima basalt covers much of the eastern edge of the Mount Aix quadrangle (Fig. 2). It consists mainly of flows but includes subordinate amounts of agglomerate and tuff. The lava is a dense, black, fresh-appearing rock. Microscopic study shows the presence of phenocrysts of calcic labradorite, augite, and olivine in a matrix of sodic labradorite, augite, and glass.[13]

The general structure of the Yakima basalt can be determined with a fair degree of accuracy even though precise dip and strike

[12] "Dioritic Intrusive Rocks and Contact Metamorphism in the Cascade Range in Oregon," *Amer. Jour. Sci.*, Vol. XXXI (5th ser., 1936), pp. 421–49.

[13] The Yakima basalt appears only slightly more mafic than the Fifes Peak andesite, and, locally, both formations may be very similar in chemical composition; but, the appearance of each is so characteristic, even in hand samples, that the two should not be confused (except where they are vitreous). The Fifes Peak andesite invariably carries stubby, tabular phenocrysts of plagioclase, which are particularly conspicuous on weathered surfaces. In the Yakima basalt only needles of plagioclase are ordinarily visible, and where larger crystals are present their tendency toward elongate shapes gives the rock a very different appearance from that of the Fifes Peak andesite.

readings can seldom be obtained. Dip slopes are common and readily recognized. These make feasible the drawing of a structure-contour map from the topographic base that gives a fairly accurate *qualitative* picture of the attitude of the Yakima basalt. Such a map, slightly

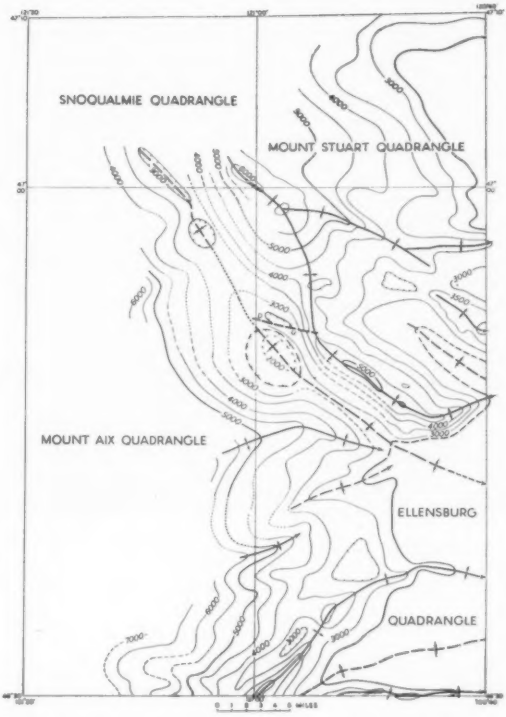

FIG. 3.—Sketch map showing structure contours on the top of the Yakima basalt. Compiled from the Geological Survey's topographic maps of the Snoqualmie, Mount Aix, Ellensburg, and Mount Stuart quadrangles, Washington. Altitudes (in feet) are above sea-level.

modified from one made by G. O. Smith,[14] is shown on Figure 3. This map shows that the surface of the Yakima basalt has been warped into an eastward-dipping slope. At its western edge in the southern

[14] "Geology and Physiography of Central Washington," *U.S. Geol. Surv. Prof. Paper 19* (1903), pp. 9–39, Pl. I.

part of the Mount Aix quadrangle the top of the basalt has a maximum altitude of 6,972 feet, while 30 miles to the east in the vicinity of Yakima its top, as indicated by drilled wells,[15] is below sea-level. The average altitude of the western edge of the Yakima basalt is about 5,000 feet.

Concurrently with the regional warping, anticlinal folds have been developed that fall into two fairly well-defined systems in which the trends are grouped around S. 55° E., and N. 70° E. Eastward these

FIG. 4.—View of north side of Tieton River Basin, showing Yakima basalt (*Ty*) overlying Fifes Peak andesite (*Tfp*) and the latter overlying the lower part of the Keechelus andesitic series (*Tlk*). Patch of Tieton andesite (*Qta*) occupies a Quaternary canyon cut in the other formations.

two trends blend into dominantly eastward-trending folds. Westward the folds tend to fade out as the margin of the basalt is approached.

The Yakima basalt is younger than the Fifes Peak andesite. This fact is not apparent in the Snoqualmie or Ellensburg quadrangles, because exposures are poor, but is easily confirmed at several places in the Mount Aix quadrangle. In a few places the contact of the Fifes Peak andesite and the Yakima basalt nearly coincides with the original margin of the Yakima basalt; but, where the larger streams cross the contact, trenching of the basalt has permitted the head-

[15] Smith, "Geology and Water Resources . . . . ," *op. cit.*, p. 53.

waters of these streams to sap the less resistant Fifes Peak andesite, so that westward-facing scarps of basalt have been formed (see Figs. 4 and 5). Even though the base of the scarp is usually mantled with talus and landslide debris, it is not difficult to see that the Fifes Peak andesite formed a rugged shore for the flood of basalt flows—a shore against which the basalt piled up to a height of at least 1,500 feet[16] in this immediate vicinity.

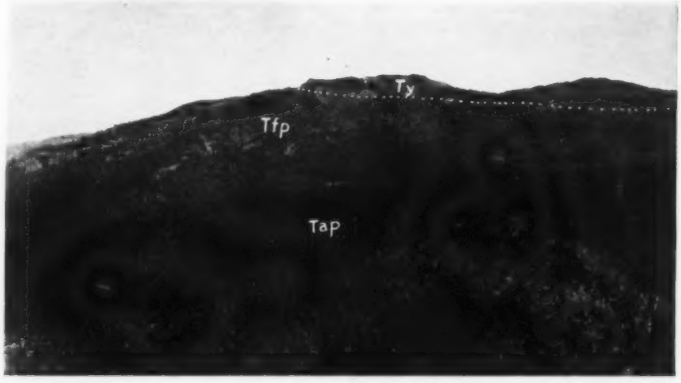

FIG. 5.—In valley of Tieton River looking eastward at escarpment of Yakima basalt (*Ty*) overlying Fifes Peak andesite (*Tfp*). Yakima basalt has a slight dip to the southeast (away from camera). Fifes Peak andesite shows initial (?) dip northward. Andesite-porphyry dike (*Tap*) outcrops in foreground and is surrounded by a mud-flow.

ELLENSBURG FORMATION

A structural basin on Naches River at the eastern edge of the Mount Aix quadrangle contains beds of conglomerate, sandstone, and shale. These beds overlie the Yakima basalt and older rocks and have been folded, though possibly not so much as the Yakima basalt. These beds are a continuation of the Ellensburg as mapped by G. O. Smith,[17] and that terminology is used here. H. E. Culver,[18]

[16] This is a net figure after making due allowance for the structure of the basalt.

[17] "Description of the Ellensburg Quadrangle," *U.S. Geol. Surv. Folio 86* (1903), pp. 2–3.

[18] "Extensions of the Ringold Formation," *Northwest Science*, Vol. XI, No. 2 (1937), pp. 57–60.

however, has recently indicated that a large part of the sediments included in the Ellensburg formation by Smith are, in reality, younger and probably belong to the Ringold formation. It is possible that both formations are also present in that part of the Mount Aix quadrangle mapped as Ellensburg.

TIETON ANDESITE

A young-appearing lava flow in the lower valley of Naches River was named the "Tieton andesite" by Smith.[19] He traced remnants of the flow (see Fig. 6) up the valley of Tieton River to the western

FIG. 6.—Remnant of Tieton andesite (*Qt*) plastered on old valley wall cut in Yakima basalt (*Ty*). View is westward in valley of Tieton River near west edge of Ellensburg quadrangle.

edge of the Ellensburg quadrangle, where he found andesitic agglomerate of similar appearance associated with the flow. In his very lucid field notes, Smith describes the relations thus:

> Massive lava lying on agglom. which extends to l. s. [last station]. The pyroclastic series dips to the S. and S.E. on both sides of the Tieton, while here and opposite on 2900′ knob fragments of flows occur, just as they do further down the canyon, except that here the and. agglom. is the rock making the canyon rather than the basalt which is seen only at the top of the S. wall of the canyon.

Smith thought that the agglomerate represented a slightly earlier phase of the Tieton volcanism which had filled a pre-existing canyon in the Yakima basalt and had, itself, been partly cleaned out before

[19] "Description of the Ellensburg Quadrangle," *op. cit.*, p. 4.

the lava flowed down the valley. Under this interpretation the agglomerate here, as well as another small area of agglomerate in the northwestern corner of the Ellensburg quadrangle, was included with the Tieton andesite.

The field relations indicated in the quotation above may, however, be interpreted to mean that three formations are present and that the basalt at the rim of the canyon caps the agglomerate, which would then be considerably older than the canyon flow of Tieton andesite. This slightly more complex interpretation is confirmed by observations in the Mount Aix quadrangle. The agglomerate can be traced directly into the Fifes Peak andesite, which is demonstrably older than the Yakima basalt; while the remnants of the Tieton flow may be traced southwestward nearly to the southern edge of the Mount Aix quadrangle, remote from the agglomerate under discussion (see Fig. 2). Furthermore, the mineralogic difference between the two andesites is greater than is suggested by field study, the feldspar of the Tieton andesite being notably more sodic.

The Tieton andesite flow has some interesting features that are pertinent to the present discussion. It has been traced for 42 miles as a single flow,[20] and its most probable source would add another 7 miles to its length. In its upper reaches it is covered with loose agglomerate, but in the lower 35 miles of its course it is essentially bare, and measurements of its gradient are there possible. For these 35 miles the flow has an average surface gradient of 75 feet per mile or less. If the lowermost 12 miles are disregarded and only the remaining 23 miles, which lie normal to the general strike of the Yakima basalt, are considered, the average gradient is 88 feet per mile. This corresponds to a dip of 1° and cannot be far from the initial gradient of the flow. On the other hand, the average dip of the Yakima basalt for much of this distance is more than 3°. Smith recognized this, for he says: "This lava was erupted after the basalt and Ellensburg rocks had been uplifted to their present positions, and at a time when the topography was essentially the same that it is today."[21]

[20] In its upper reaches it is joined by other flows.

[21] "Geology and Physiography . . . . ," *op. cit.*, p. 18.

However, the topography in the upper part of the Tieton Valley has changed considerably since the extravasation of the Tieton andesite. A deep glacial valley has been cut through the Tieton flow and the rocks beneath, and the post-lava drainage is markedly different from the pre-lava drainage. The glaciation is alpine and hard to date but is probably not later than the last stage of continental glaciation. Consequently, the age of the Tieton andesite is either interglacial or preglacial, and the folding of the basalt is somewhat earlier.

Other late flows are present near the crest of the Cascade Mountains but are not believed to be pertinent to the present discussion.

COLLUVIUM

Pyroclastic materials overlain by more resistant formations are notorious for landslides and mudflows. Both are very common in the Mount Aix quadrangle along the contact between the Yakima basalt and the Fifes Peak andesite. For the sake of clarity, these, as well as small amounts of alluvium and glacial deposits, have been omitted from the map accompanying this paper.

CORRELATION

No new evidence on the age of the Yakima basalt is presented in this paper except that the Yakima basalt is younger than the Fifes Peak andesite (or Keechelus andesitic series). The Yakima basalt is generally agreed to be Miocene, but its location within that period is by no means settled. Its close relation to the Ellensburg formation, commonly regarded as Upper Miocene,[22] leads me to regard the Yakima basalt *in this area* as Upper Miocene, also. However, both age assignments leave much to be desired, and the following suggestions as to the age of the Fifes Peak andesite and the lower Keechelus must inherit this uncertainty.

AGE OF THE FIFES PEAK ANDESITE

The ruggedness of the surface between the Fifes Peak andesite and the overlying Yakima basalt is not good evidence of any great lapse of time between the two, since the Fifes Peak volcanism probably produced a surface that was highly irregular from the start. Overlap of the Yakima basalt onto formations older than the Fifes Peak an-

[22] Wilmarth, *op. cit.*, p. 674.

desite is scarcely better evidence of unconformity; nor is discordant structure conclusive evidence in this area of high initial dips in the andesite.

In the absence of fossils, lithologic correlations afford the best hope of dating the Fifes Peak andesite. On this basis correlation with the Taneum andesite is one possibility. In the Mount Stuart quadrangle the Taneum andesite underlies the Yakima basalt and was given its name to distinguish it from "other andesites of similar composition, although of different age, which occur in adjoining quadrangles."[23] This reference was principally to the Keechelus andesitic series, which was supposedly younger than the Yakima basalt. But evidence has been presented in this paper that the Keechelus andesitic series is older than the Yakima basalt, and there is little doubt that the Taneum andesite is equivalent to some part of the Keechelus. Smith's description of the Taneum andesite suggests a lithology more typical of the Fifes Peak andesite (upper Keechelus) than of the lower Keechelus. This suggested similarity is fortified by the proximity of the Taneum andesite to outcrops of the Fifes Peak andesite. Smith regarded the Taneum andesite as Miocene.

The Fifes Peak andesite disappears in the southern part of the Mount Aix quadrangle, but it reappears farther south, in the Mount Adams quadrangle, on the headwaters of Klickitat River and extends an unknown distance southward. Still farther south, in the Columbia River gorge, the Eagle Creek formation is overlain with slight unconformity by the Columbia River basalt. E. T. Hodge describes the Eagle Creek formation (in part) as follows:

> The Eagle Creek formation is composed entirely of volcanic materials such as tuffs, breccias, agglomerates, and lava flows. . . . .
>
> All the rocks of the Eagle Creek formation are vitrophyric, fine-grained or porphyritic. In order of importance the lava types are as follows: pyroxene andesite, hornblende andesite, trachyandesite, pyroxene trachyte, pyroxene basalt, hornblende basalt, and olivine andesite. . . . .
>
> The composition, the change in physical character of this material from place to place, the structure, the preserved surface, and the position of the fossils in the

[23] Smith, "Description of the Mount Stuart Quadrangle," *U.S. Geol. Surv. Folio 106* (1904), p. 7.

Eagle Creek formation all indicate that it is the south slope of a volcano that has been partially buried by the Columbia River basalts and only slightly deformed. . . . .[24]

The striking similarity in stratigraphy and lithology of this formation to the Fifes Peak andesite is strongly suggestive of contemporaneity. Hodge believes that the Eagle Creek formation is probably Lower Miocene,[25] whereas R. W. Chaney now believes that the flora of the Eagle Creek formation is Middle Miocene.[26]

AGE OF THE LOWER PART OF THE KEECHELUS

In the Snoqualmie quadrangle the Keechelus andesitic series unconformably overlies several well-known Eocene formations and the Guye formation. The Guye formation was assigned a Miocene age by Knowlton, but Smith and Calkins apparently were not entirely satisfied with this assignment, for they say:

Yet the stratigraphic relations to the overlying rocks, added to the lithologic resemblance of the Guye formation (composed of interbedded sediments, basalt, and rhyolite) to the Eocene formations, would have led to its reference to the Eocene were it not for the paleobotanic evidence just cited.[27]

The paleobotanic evidence was based on a small plant collection from which Knowlton identified two Miocene forms, *Platanus dissecta* Lx., and *Acer aequidentatum* Lx.; a *Ficus* very similar to the Paleocene *F. artocarpoides* Lx.; and a new species of *Cinnamomum*.

Dr. Roland W. Brown, of the Geological Survey, has been so good as to inspect the original collection recently, and he informed me orally that the two supposed Miocene forms probably represent leaf variations of a single species, probably ancestral to *Platanus dissecta* Lx. He considers the *Ficus* too fragmentary to identify satisfactorily, but the excellent specimens of *Cinnamomum* are very similar to, if not identical with, *C. dilleri* Kn., from the Comstock flora[28] of western Oregon.

[24] "Geology of the Lower Columbia River," *Bull. Geol. Soc. Amer.*, Vol. XLIX (1938), p. 846.

[25] *Op. cit.*, pp. 843–45.

[26] "The Succession and Distribution of Cenozoic Floras around the Northern Pacific Basin," *Univ. Calif. Essays in Geobotany* (1936), p. 74.

[27] *Op. cit.*, p. 7.

[28] E. I. Sanborn, "The Comstock Flora of West Central Oregon," *Carnegie Inst. Wash. Publ. No. 465* (1935), pp. 1–28.

Chaney, in a recent summarization, lists both *Cinnamomum* and *Ficus* as index fossils for the Eocene.[29]

As thus reinterpreted the paleobotanical evidence supports the stratigraphic evidence of an early Tertiary age for the Guye formation. If the Eocene age of the Guye formation be conceded, the lower Keechelus unconformably overlies Eocene rocks and unconformably underlies Miocene rocks, suggesting an Oligocene age for the lower Keechelus.[30]

PHYSIOGRAPHY

Not enough evidence has been obtained in the Mount Aix quadrangle to reconstruct the physiographic conditions during the early part of the Tertiary, but the record is clearer for the latter part. A. C. Waters [31] has described a mature erosion surface in northern Washington which is older than the Columbia River basalt but truncates folded sediments and pyroclastics of early Tertiary age. This surface may be correlative with the surface developed in the Mount Aix quadrangle on the folded lower Keechelus and older rocks.

On this surface, during the early or Middle Miocene, a chain of volcanoes erupted the lavas and pyroclastic materials of the Eagle Creek formation, the Fifes Peak andesite (or upper Keechelus), and the Taneum andesite. The resultant topography seems to have been hilly rather than mountainous.

Beginning in the Middle Miocene or somewhat later, outpouring of the "plateau basalts" began in the region to the east in a manner concisely described by I. C Russell:

> The lava came through fissures in the earth's crust . . . . and spread widely over the land, from which it is evident that each sheet was spread out horizontally. . . . . Although the lava sheets are still essentially horizontal over broad

[29] *Op. cit.*, p. 59.

[30] When this paper was presented at the June, 1940, meeting of the American Association for the Advancement of Science, Mr. Robert Y. Grant, of the University of Washington, informed me that he had found the lower jaw of an oreodont in Tieton River in beds mapped by me as lower Keechelus. The fossil has been identified as Eporeodon, common in the John Day formation of Oregon and which has a probable range from Middle Oligocene to Lower Miocene. Mr. Grant is preparing a paper for publication on his valuable discovery.

[31] "Resurrected Erosion Surface in Central Washington," *Bull. Geol. Soc. Amer.*, Vol. L (1939), pp. 635–60.

areas, they frequently have gentle dips, and in certain regions are tilted and even sharply folded and faulted. On the eastern slope of the Cascade Mountains the lava sheets occur with a dip to the eastward, for long distances, of 3 or 4 degrees, showing that a large part of that range has been elevated to a height of at least 6,000 feet since the lava was poured out.[32]

On page 53, Russell continues:

As already explained, the Columbia River lava was poured out in a molten condition, in a series of vast inundations, over a deeply eroded land surface. The contact of the lava with the formations on which it rests is always unconformable, and between the two there are no massive sediments. As the pile of lava sheets is in places more than 4,000 feet thick, it follows that the last sheet spread out must have had at least that elevation above the sea, unless the old land surface, like the region about the Dead Sea and the bottom of Death Valley at the present day, was below sea level, which is improbable. The only other escape from the conclusion just stated seems to be that movements producing a depression occurred during the time the lava sheets were being formed. If such a downward movement did occur, it was evidently not sufficient to carry the surface below sea level for no marine sediments have been discovered between the lava sheets.

That such depression did take place concurrently with the extrusion of the lava is strongly suggested by the following facts.[33] At Pullman, Washington, near the eastern margin of the basalt, the altitude of the surface of the basalt is about 2,500 feet above sea-level; in the Oakesdale quadrangle, between Pullman and Spokane, it is from 2,250 feet to 2,600 feet;[34] and in the vicinity of Spokane,[35] it is from 2,400 feet to 2,600 feet. In the Okanogan quadrangle to the west, the topography indicates that the basalt surface varies from about 2,500 feet to 3,000 feet above sea-level. In each of these areas the dip of the basalt surface is toward the center of the Columbia River Basin, suggesting that some depression has taken place; but the uniformity of altitude over so great an extent also suggests that the amount of this depression has not been large. The altitude

[32] "Geology and Water Resources of Nez Perce County, Idaho," *U.S. Geol. Surv. Water Supply Paper 53* (1901), p. 29.

[33] I am indebted to Sheldon L. Glover for suggesting this line of evidence.

[34] V. E. Barnes, "Geology of the Oakesdale Quadrangle" (Master's thesis [1927]). (Manuscript copy in the Washington State College Library, Pullman.)

[35] J. T. Pardee and Kirk Bryan, "Geology of the Latah Formation in Relation to the Lavas of the Columbia Plateau near Spokane, Wash.," *U.S. Geol. Surv. Prof. Paper 140* (1926), p. 11.

of the basalt surface along this marginal tract was probably never much more than 3,000 feet above sea-level. A similar altitude for the western margin of the Yakima basalt near the close of the Miocene volcanism seems reasonable.

Even before the last basalt flow was extruded, streams from the hills to the west began to flow onto the basalt plain and deposit the sediments of the Ellensburg formation. Deposition at first was probably localized in depressions at the edges of the lava flows, and then later in structural basins due to folding of the basalt, concurrently with the uplift of the Cascade Mountains. This uplift is indicated by the abundance of material in the Ellensburg formation which has been furnished by rocks belonging to the lower part of the Keechelus series and which would not be available in such quantity without deformation of the area in which they occur. As Smith has pointed out, this deformation was sufficiently slow for the Yakima River to maintain its course normal to the trend of the anticlinal ridges.[36]

Smith has indicated that two periods of post-basalt deformation, separated by a period in which the area was reduced to baselevel, are demonstrated in this area,[37] but Waters[38] and J. P. Buwalda[39] have reviewed Smith's evidence and concluded that but one period of deformation and no reduction to baselevel is required by the evidence. One protracted period of deformation seems to be sufficient to explain all the field relations here, but the problem deserves more study.

Altitudes along the western margin of the Yakima basalt confirm Russell's statement (see above) that a large part of the Cascade range has been elevated to a height of at least 6,000 feet above sea-level. Because the basalt does not reach to the crest of the range in the area studied, an accurate estimate of the original height is possible only in a few localities. In the southern part of the Snoqualmie quadrangle, where nearly flat-topped remnants of the Fifes Peak andesite appear to have been but slightly eroded, the altitudes vary from about 5,000 feet to 6,000 feet above sea-level. In the southern

[36] "Geology and Physiography . . . . ," *op. cit.*, p. 32.

[37] *Ibid.*, p. 21.

[38] *Op. cit.*, pp. 643–44.

[39] "Postulated Peneplanation in Central Washington," abstr., *Proc. Geol. Soc. Amer.*, *1935* (1936), pp. 331–32.

part of the Mount Aix quadrangle the margin of the basalt has an altitude of nearly 7,000 feet, and the axial portion of the range may have been several thousand feet higher, unless erosion kept pace with the uplift.

The uplift of the range appears to have been completed by the early part of the Pleistocene, when the Tieton andesite and other Quaternary volcanics were extruded. Except for the well-known volcanic peaks of Washington—Mount Baker, Glacier Peak, Mount Rainier, Mount St. Helena, and Mount Adams—the post-Yakima volcanism does not appear to have been quantitatively important in Washington.

ACKNOWLEDGMENTS.—Although I take full responsibility for the opinions expressed in this paper, many friends have contributed generously of their time and criticism, and the paper is the better for their help.

I wish particularly to thank Dr. Harold E. Culver for encouraging and directing these studies and Dr. Roland W. Brown for reviewing the Guye flora. Frank C. Calkins' many suggestions during the preparation of this paper have placed me deeply in his debt.

RECENT GLACIER RECESSION IN GLACIER NATIONAL PARK, MONTANA

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ABSTRACT

The magnitude of recent glacier recession in this area has been brought to light by means of detailed mapping of several of the larger glaciers and examination of many others. Results indicate that since the beginning of the present century some of the principal glaciers have been reduced 40–75 per cent in area and more in volume. Several smaller glaciers have nearly or entirely disappeared during the same interval; and in a warm, dry summer all snow from the previous winter is dissipated from the firn areas or zones of accumulation on nearly all the glaciers.

INTRODUCTION

In August, 1937, the National Park Service embarked upon a program of glacier mapping in Glacier National Park, with the preparation of a map of Grinnell Glacier on a scale of 1:2400.[1] Subsequently, similar detailed topographic maps were made of Sperry (August, 1938) and Jackson (August, 1939) glaciers. It is planned to remap these bodies of ice every five years so that an accurate check may be made upon their decrease in area and in volume. The approximate locations of the glacier borders when first mapped (1900–1904) have been determined by means of photographs, some of which were taken as early as 1897,[2] together with the Chief Mountain and Kintla Lakes topographic sheets of the United States Geological Survey, and by careful examination of the glaciers and their bordering moraines by the writer during the summer seasons of 1935–40, inclusive. The Survey's maps, on a scale of 1:125,000, are, in most cases, too generalized to serve alone as the basis for outlining these glaciers, but the addition of photographs taken at or about the time of the first mapping makes a fair degree of accuracy possible.

[1] George R. Gibson and James L. Dyson, "Grinnell Glacier, Glacier National Park, Montana," *Bull. Geol. Soc. Amer.*, Vol. L (1939), p. 682.

[2] Albert L. Sperry, *Avalanche* (Boston: Christopher Publishing Co., 1938). Several interesting photographs of Sperry and other glaciers appear in this book. Additional ones, not appearing in the book but taken during the same period, are in the possession of Mr. Sperry.

RECESSION OF INDIVIDUAL GLACIERS

GRINNELL GLACIER

The glacier when mapped in 1900–1902 had a surface area of approximately 0.93 square mile. This value was derived from the small-scale Survey map and consequently is not very accurate. The area may have been larger, for W. C. Alden[3] states that in 1911 its area was slightly greater than 1 square mile. At the time of mapping it consisted of a lower main section, the headward portion of which

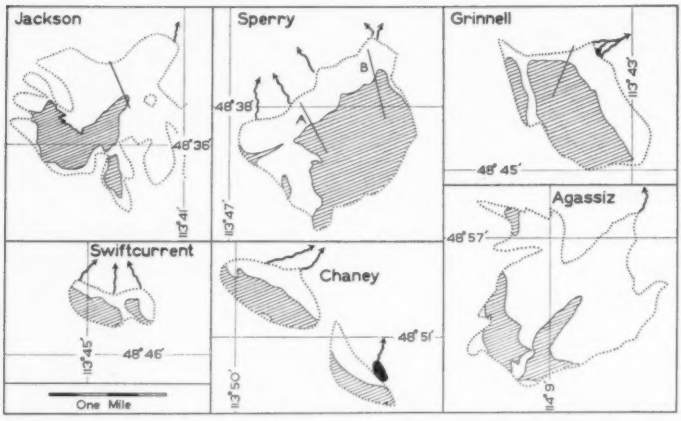

FIG. 1.—Sketch maps showing decrease in area of several glaciers in Glacier National Park. Scale is same for all maps. Dotted lines represent glacier borders when the region was mapped by the United States Geological Survey (1900–1904). Cross lines indicate approximate areas of glaciers in 1940. Lines showing location of sections in Fig. 2 are also indicated.

was connected to a smaller section lying on a shelf somewhat higher on the cirque headwall. The connection between these two parts, although dwindling in size, persisted until about 1929 when it disappeared, thus severing Grinnell Glacier into two separate parts. The lower of the two when mapped in 1937 possessed a surface area of 0.51 square miles and the upper, although not mapped, was estimated to have a much smaller area, probably not greater than 0.04 or 0.05 square miles. Thus between 1900–1902 and 1937 the total area of Grinnell Glacier suffered a decrease of at least 40 per cent (Fig. 1).

[3] *Glaciers of Glacier National Park* (Washington: U.S. Dept. Int., 1914), p. 19.

Volume shrinkage of the ice apparently has been even greater. It has been possible by examining cirque floors around the edges of glaciers recently mapped and measuring depths of crevasses and moulins to determine roughly the attitude of the cirque floor beneath

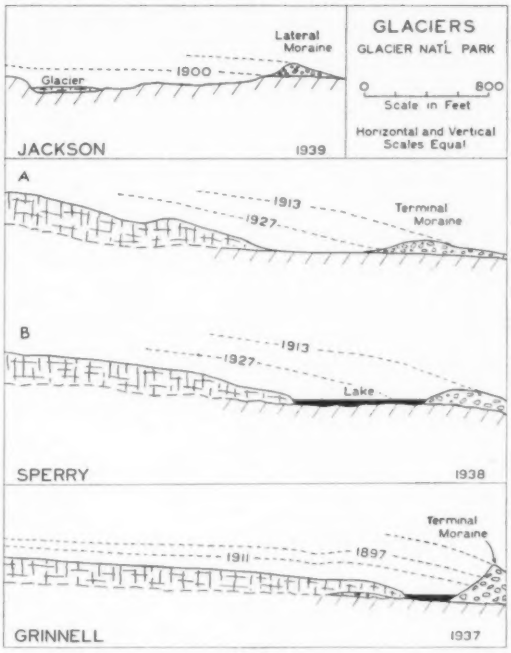

FIG. 2.—Sections across terminal portions of glaciers which recently have been mapped in detail. Dashed lines show approximate level of ice surface at earlier dates. The date of most recent mapping appears on the right underneath each section. For location of sections see Fig. 1.

the ice. Thus a figure for the probable thickness of the ice has been determined. If estimates of the thickness of Grinnell Glacier are approximately correct, the ice since 1900–1902 has lost 50 per cent or more of its volume. A profile constructed with the aid of the 1937 map and a photograph taken in 1897 indicates that the glacier at the earlier date was about 300 feet thick at a point where the northern terminus of the ice lay in 1937 (Fig. 2). Alden in 1911[4] found

[4] *Ibid.*, p. 19.

that the ice was from 80 to more than 100 feet thick at the same site. When the glacier possessed the maximum size allowed by the innermost of the moraines surrounding it, presumably as late as 1850,[5] its thickness here must have been 350–400 feet. The ice since then must have decreased considerably more than 50 per cent in volume.

SPERRY GLACIER

This glacier, at present the largest single ice mass in Glacier National Park, possessed a surface area of approximately 1.31 square

FIG. 3.—Front of Sperry Glacier looking northeast, August 16, 1913. Photograph (716) by W. C. Alden, courtesy U.S. Geol. Surv.

miles[6] in 1900–1902. Between that time and August, 1938, shrinkage caused the glacier to separate into one main and several smaller ice masses. The surface area of the former was 0.61 square mile, only about 47 per cent of the area in 1900–1902.

The present terminus of the glacier now lies at a distance varying between 600 and 1,400 feet from the inner side of a conspicuous and

[5] F. E. Matthes, "Report of the Committee on Glaciers," *Amer. Geophys. Union, Trans. of 1939*, Part IV, p. 518; also "Report of Committee on Glaciers," *Amer. Geophys. Union, Trans. of 1940*, Part II, p. 400.

[6] This figure was determined from the Chief Mountain, Montana, topographic sheet of the United States Geological Survey.

comparatively wide terminal moraine (Figs. 2 and 4). In 1900–1902 the ice front lay near the outer margin of this moraine, and in 1913 still rested upon the top of the moraine but near its inner edge (Figs. 2 and 3). At that time, when the portion of the cirque floor

FIG. 4.—Front of Sperry Glacier looking northeast, August 22, 1940. In 1913 (Fig. 3) the ice front rested on crest of moraine at left side of photograph. The moraine has a height of 70 feet.

inside the moraine was entirely covered with ice, the glacier over most of its area certainly was several hundred feet thicker than at present.

JACKSON GLACIER

On the Chief Mountain, Montana, Quadrangle map "Blackfoot Glacier" is the name applied to two small ice masses which, although

joined, were in 1901 two separate glaciers.[7] Recently the name "Jackson" has been adopted as the official designation of the westernmost of the two. In 1901 this glacier possessed an area of about 1.25 square miles and a length of 1.5 miles. Detailed mapping in August, 1939, showed that Jackson Glacier had shrunk until its area was only 0.29 square mile and its length 1 mile. One-half mile of exposed rock surface separated the two glaciers at the site of the former ice connection. Although Jackson Glacier even in 1901 was comparatively thin (Fig. 2), it was then about 200 feet thick where the ice ended in 1939.

The top slope of Jackson Glacier is practically the same as the slope of the bedrock surface from which it has receded during the last forty years. This, plus the fact that portions of the cirque floor are beginning to emerge near the head of the glacier, leads to the conclusion that Jackson Glacier is very thin, probably possessing a nearly uniform thickness throughout.

AGASSIZ GLACIER

Of all the park's principal glaciers, Agassiz in recent years probably has undergone the most phenomenal reduction in size. Although at the turn of the century it was one of the two largest glaciers, it since has shrunk to a position of relative unimportance.

Since 1932 recession of the tongue of this glacier has been measured annually by the National Park Service. During the six-year period, 1933–38, inclusive, the terminus receded a total distance of 655 feet.[8] Even though large, this figure is not indicative of the total recession or volume shrinkage of the glacier. In the fall of 1937 Agassiz Glacier was found to be almost severed into two parts,[9] and between then and September 9, 1940, when the glacier was visited by the writer, the separation had become complete, as on that date there were two separate, nearly equal-sized bodies of ice (Fig. 5). The easternmost had the form of a distinct tongue, the long axis of which coincided roughly with the median line of the former, much

[7] Matthes, personal communication.

[8] "Reports of the Committee on Glaciers," *Amer. Geophys. Union Trans.* (1937 and 1939).

[9] "Report of the Committee on Glaciers," *Amer. Geophys. Union Trans.*, Part IV (1939), p. 522.

larger Agassiz Glacier. The length of the tongue was slightly less than seven-eighths of a mile, in contrast to a length of one and three-fourths miles possessed by Agassiz Glacier when mapped in 1902–4.[10] The other body of ice, which is slightly larger, lies at a higher elevation just to the west at the base of Kintla Peak. These ice masses are entirely independent of each other, the higher of the two supplying no ice to the lower (Figs. 1 and 5).

FIG. 5.—Agassiz Glacier from the northeast, September 9, 1940. Kintla Peak on right. Compare this view with that taken by Alden in 1913 (Fig. 6).

When examined in the fall of 1940, all snow which had accumulated during the previous winter had disappeared from the lower of the two ice masses while only scattered small patches remained on the upper.

Agassiz Glacier, including a small contiguous body at its northwest edge which probably supplied little or no ice to the main glacier, had, when mapped by the United States Geological Survey,[11] an area of about 1.40 square miles, but in the fall of 1940 the combined surface areas of the two small remnants amounted to only 21 per cent (0.29 square mile) of this amount (Fig. 1).

Volume shrinkage was even greater because of a tremendous low-

[10] *Kintla Lakes Quadrangle (1902–4)*, U.S. Geol. Surv. [11] *Ibid.*

ering of the surface by ablation. Examination of the area from which this glacier has recently retreated indicates that when the ice terminus lay near the crest of the inner moraine, between 50 and 100 years ago, the ice of the main tongue was several hundred, possibly as much as 700 or 800, feet thick near a site from which the ice has since disappeared. Today it is doubtful if the ice anywhere much exceeds 30 or 35 feet in thickness. This is further attested by the exposure of the cirque floor (a dip slope) at several places within both ice masses (Fig. 5). As late as 1913 practically all of the cirque floor

FIG. 6.—Agassiz Glacier from the northeast, August 5, 1913. Photograph (705) by W. C. Alden, courtesy U.S. Geol. Surv.

within the innermost moraine was covered by ice (Fig. 6). At that time the ice tongue extended to a point beyond the bottom of Figure 5, covering the re-entrant cliff over which the melt-water stream falls.

GLACIER AT ICEBERG LAKE

A glacier infrequently cited in the literature on glacier recession is the small body of ice at Iceberg Lake, which lies in one of the most conspicuous cirques in Glacier National Park, and drains into Swiftcurrent Valley through Wilbur Creek. Since establishment of the park in 1910, Iceberg Lake, because of the presence of numerous

bergs furnished by "Iceberg Glacier,"[12] has been one of the chief attractions of the Swiftcurrent region. Throughout each summer from early July until the lake froze in the fall, its surface was at all times dotted with icebergs varying from a few feet to 100 or 200 feet in length. In 1911 Alden[13] found that the glacier extended from the cirque wall a considerable distance out into the lake, and in 1920, although the glacier did not extend so far into the lake, it ended in a sheer cliff rising 90–100 feet[14] above the surface of the water. Early in July, 1935, when first viewed by the writer, the surface of Iceberg Glacier merged imperceptibly with the frozen lake surface. Lowering of the glacier surface by ablation had completely eliminated the ice cliff which 15 years earlier attained a height of more than 90 feet.

In the summer of 1940 the glacier not only was considerably smaller than in 1935 but had so shrunk that it no longer was in contact with the lake. It appeared to be no more than a small mass of granular snow-ice clinging to the base of the cirque wall west of the lake. Although numerous bergs were present in the lake until mid-August, they probably were composed mainly of lake ice or compacted snow which had drifted onto the frozen surface of the lake during the preceding winter. A large proportion of the early-summer bergs always were of these types. Nevertheless, on August 31, 1940, not a single berg or body of compacted snow was present in the lake. So far as known this is the first time that Iceberg Lake has been completely free of icebergs. Further, the lake which in 1935 possessed a chalky blue color because of an abundance of rock flour, has gradually been assuming more of a bluish tint as rock flour becomes less and less concentrated.

ADDITIONAL FACTS AND INFERENCES

Not only the few glaciers listed above, but all those in Glacier National Park, have been undergoing pronounced recession in re-

[12] This very small ice mass which lies at the head of the cirque adjacent to the lake has never been officially named. It is here called "Iceberg Glacier" for the sake of convenience.

[13] *Op. cit.*, p. 23.

[14] Alden, oral statement to the writer.

cent years. Several of the smaller ones, most notable of which is "Clements Glacier,"[15] at the east base of Clements Mountain (lat. 48° 42′ N.; long. 113° 44′ W. on the Chief Mountain, Montana, Quadrangle), have entirely disappeared. Other glaciers, principally Harrison, Kintla, and Blackfoot, which were among the area's most important years ago, have been reduced to pitiable remnants.

Ordinarily ablation, which decreases from a maximum at the ice margin to a minimum at the cirque headwall, is not sufficient to remove from the firn area all snow which accumulated during the previous winter. But during the past several years, particularly since 1935, firn areas of these glaciers have been getting noticeably smaller, and in early September, 1940, the snow from the previous winter had been entirely dissipated from the firn areas of most of the Park glaciers. In other words, ablation had been so pronounced that each glacier lay entirely within the zone of dominant wastage. The summer of 1940 was marked by unusually high temperatures and the previous winter by abnormally light snowfall, but unless a general climatic change occurs within the next ten or fifteen years, it seems quite probable that such thin masses of ice as Jackson and Agassiz glaciers will disappear.

[15] Max Demorest, "Ice Flowage as Revealed by Glacial Striae," *Jour. Geol.*, Vol. XLVI (1938), p. 702. The map of Clements Glacier made in August, 1937, depicts also the terminal moraine, the area in back of which presumably was entirely covered by ice in 1900–1902.

METAMORPHISM OF A ROOF PENDANT OF THE IDAHO SPRINGS FORMATION FRONT RANGE, COLORADO

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Houston, Texas

ABSTRACT

A roof pendant of the Idaho Springs formation near Allens Park, Colorado, consists of a granite injection gneiss, a hornblende-plagioclase gneiss, and a thick series of lime-silicate rocks composed of varying amounts of grossularite, diopside, calcite, vesuvianite, wollastonite, and quartz. Erosion has left the roof pendant as an isolated body in a region consisting chiefly of pre-Cambrian granite. Field and petrographic study favors the conclusion that the rocks were formerly calcareous and dolomitic sedimentary rocks of varying impurity that have been subjected first to regional metamorphism and later to contact metamorphism.

INTRODUCTION

An isolated roof pendant of the Idaho Springs formation is located five miles east of Allens Park, Boulder County, Colorado, in a region composed largely of the Silver Plume (Longs Peak[1]) granite of Archean age. The roof pendant is of particular interest because it consists of three distinct lithologic members: (1) lime-silicate rock containing varying amounts of grossularite, diopside, calcite, vesuvianite, wollastonite, and quartz; (2) hornblende-plagioclase gneiss; and (3) granite injection gneiss. The writer has been unable to find any published description of this small but interesting area. The area is locally known as the "Dry St. Vrain region" because of its proximity to Dry St. Vrain Creek. The roof pendant lies mostly within the E. $\frac{1}{2}$ of N.E. $\frac{1}{4}$ Sec. 26 and the W. $\frac{1}{2}$ of N.W. $\frac{1}{4}$ Sec. 7, township 3 N., range 72 W. Most of the field work was done during the summer of 1934.

IDAHO SPRINGS FORMATION

The roof pendant is part of the Idaho Springs formation. The term "Idaho Springs" was proposed by Ball,[2] and it was used to

[1] M. F. Boos and C. M. Boos, "Granites of the Front Range—the Longs Peak–St. Vrain Batholith," *Bull. Geol. Soc. Amer.*, Vol. XLV (1934), pp. 303–32.

[2] S. H. Ball, J. E. Spurr, and G. H. Garrey, "Economic Geology of the Georgetown Quadrangle, Colorado," *U.S. Geol. Surv. Prof. Paper 63* (1908), p. 37.

designate "a series of interbedded metamorphic rocks, presumably of sedimentary origin, which are typically exposed in the vicinity of Idaho Springs," Colorado. E. S. Bastin and J. M. Hill[3] later accepted this formation name for rocks of the same characteristics that occur in parts of Boulder, Clear Creek, and Gilpin counties.

The lithology of this formation is extremely variable both locally and regionally. P. G. Worcester[4] has identified garnetiferous quartz-mica schist, sillimanite schist, quartz-mica schist, and hornblende schist in the Ward region, which he states are all probably phases of the Idaho Springs formation. In the Georgetown quadrangle Ball[5] recognized biotite-sillimanite schist, biotite schist, quartz gneiss, ellipsoidal masses of quartz and sillimanite, and lime-silicate rocks. The Big Thompson schist[6] is typically exposed fifteen miles north of the Dry St. Vrain area in Big Thompson Canyon. This metamorphic aureole of the Idaho Springs formation includes biotite-sillimanite schist, biotite-chlorite schist, and quartz schist; all presumably of sedimentary origin. T. S. Lovering[7] has presented a concise summary of the pre-Cambrian events in the Front Range in Colorado, and he states that the less altered facies of the Idaho Springs formation consist chiefly of quartz-biotite schists, biotite-sillimanite schists, and quartz schists or gneisses, with occasional masses of lime-silicates intergrown with garnet and magnetite; the latter suggesting the metamorphism of limy beds.

Some of the schists and gneisses composing the Idaho Springs formation have undoubtedly resulted from the metamorphism of igneous rocks, although it is generally believed that the formation has been derived chiefly from argillaceous sediments.

[3] "Economic Geology of Gilpin County and Adjacent Parts of Clear Creek and Boulder Counties, Colorado," *U.S. Geol. Surv. Prof. Paper 94* (1917), p. 26.

[4] "Geology of the Ward Region, Boulder County, Colorado," *Colo. Geol. Surv. Bull. 21* (1920), pp. 21–23.

[5] *Op. cit.*, pp. 38–43.

[6] M. B. Fuller (M. F. Boos), "Contact Metamorphism in the Big Thompson Schist of Northern Colorado," *Amer. Jour. Sci.*, Vol. XI (5th ser., 1926), pp. 194–200.

[7] "Geologic History of the Front Range, Colorado," *Proc. Colo. Sci. Soc.*, Vol. XII, No. 4 (1929), pp. 63–74.

STRUCTURE OF THE ROOF PENDANT

The roof pendant is an irregularly-shaped mass that trends nearly north-south (Fig. 1). It has an exposed length of 3,200 feet and an

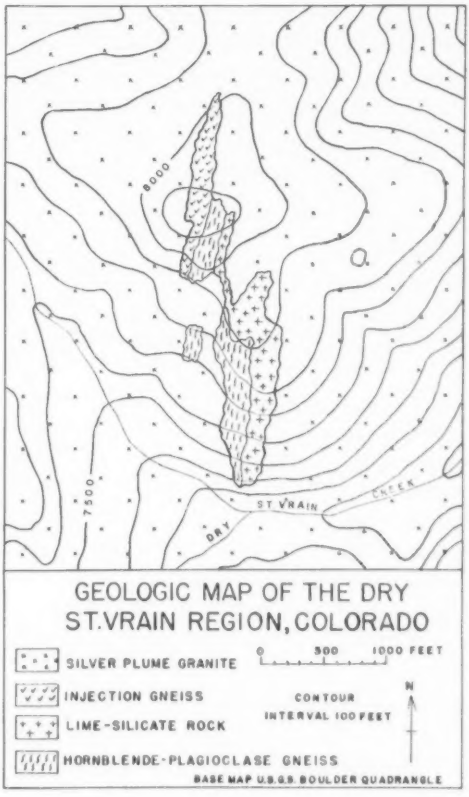

FIG. 1

average width of 400 feet. The attitude of the formation varies considerably because of much minor folding and faulting, although the regional structure is still definitely distinguishable, and the beds have an average strike of N. 16° E. and an average dip of 65° E. The angle

of dip is more consistent than the strike. This mass of rock is assumed to be a roof pendant rather than a xenolith because of its large size and the fact that its attitude conforms in general to the attitude of the Idaho Springs formation in adjacent areas.

An outstanding field relationship between the various rock types is that they are roughly arranged in three distinct zones (Fig. 1) with the injection gneiss occupying the western border of part of the mass, the hornblende-plagioclase gneiss occupying the central zone, and the lime-silicate rock bordering the mass on the east.

ROCKS OF THE REGION

SILVER PLUME GRANITE

The Silver Plume granite is the most abundant rock of the Dry St. Vrain region, and outcrops are numerous. The typical granite is flesh-colored, moderately coarse-grained, and porphyritic with the feldspar phenocrysts commonly occurring in subparallel positions. The phenocrysts, ranging from 6 mm. to 12 mm. long, are microcline and orthoclase, commonly twinned according to the Carlsbad law. The groundmass consists chiefly of quartz, orthoclase, microcline, andesine, muscovite, and biotite. In thin section the granite is seen to have a cataclastic structure as evidenced by the deformation of the grains, the irregularity of the microcline grating, marked undulatory extinction of the quartz, and the subparallel alignment of the phenocrysts. The great amount of injection of the granite into the Idaho Springs formation in this and other localities indicates further that there was considerable movement and pressure during its crystallization.

Pegmatite dikes and quartz veins genetically related to the granite are abundantly found penetrating the roof pendant. They are particularly abundant in the southern part of the mass where some of the veins are slightly mineralized and have been prospected for copper although containing only a small amount of chalcopyrite, malachite, and hematite.

GRANITE INJECTION GNEISS

The granite injection gneiss is best exposed in the northwestern part of the roof pendant. It is a typical injection gneiss formed by the lit-par-lit injection of the magma of the Silver Plume granite be-

tween the foliation leaves of a former mica schist. The appearance of the gneiss varies considerably owing to the difference in the blending of the dark biotite-rich bands and the lighter felsic bands. The felsic bands commonly range from 2 mm. to 15 mm. in thickness, although in places they are more than a meter thick. The dark bands have a wavy character, although pronounced contortion is not common. The degree of soaking and injection by the granitic magma and the resultant distribution of the biotite and its associated minerals vary greatly in different parts of the mass. Microscopic examination of several thin sections of the rock shows that the felsic material is chiefly quartz and orthoclase, accompanied by minor amounts of oligoclase, microcline, apatite, and sphene. The dark bands are chiefly composed of anhedral grains of brown, pleochroic biotite associated with small amounts of wavy, felted masses of sillimanite fibers. Irregular grains of magnetite derived from the biotite are locally abundant.

HORNBLENDE-PLAGIOCLASE GNEISS

The hornblende-plagioclase gneiss is the best-exposed member of the roof pendant. The rock is composed chiefly of hornblende and labradorite. It is greenish black, fine-grained, and fairly uniform in appearance and average composition. The structure varies from a gneissic to a schistose character with the former predominating due to slight concentrations of hornblende or plagioclase into bands which vary considerably in thickness but average 5 mm.

Numerous felsic dikes cut the rock parallel to the gneissic structure, although some cut the structure at various angles. The felsic material is genetically related to the Silver Plume granite, and it was injected along pre-existing lines of weakness. The essential minerals of the dikes are quartz and orthoclase, and the accessory minerals are oligoclase and sphene. The dikes have locally produced a marked change in the appearance and mineralogical composition of the gneiss by altering the dark-colored hornblende to a lighter green-colored pyroxene intermediate in composition between diopside and hedenbergite. These layers accentuate the gneissic banding of the rock.

A microscopic examination of fourteen thin sections of the gneiss collected at widely separated localities shows an average mode by

volume of 46 per cent hornblende, 42 per cent plagioclase, and a total of 12 per cent for the accessory minerals orthoclase, hedenbergite, quartz, sphene, and apatite. Hornblende occurs as roughly elongated, anhedral (rarely subhedral) grains about 1 mm. in length that are arranged in a subparallel position. The maximum extinction angle ($Z \wedge c$) is 19°; pleochroism is prominent with X = pale green, Y = bluish green, Z = dark green. The plagioclase is somewhat variable in composition in different parts of the area although averaging an intermediate labradorite. The grains average 0.8 mm. in length and are likewise characteristically anhedral in shape. It is noteworthy that all the accessory minerals show a marked increase in abundance near the contact with the felsic dikes and also near the contact of the gneiss with the bordering granite. Near the center of the mass some specimens are entirely lacking in accessory minerals.

LIME-SILICATE ROCK

The lime-silicate rock is the most variable member of the roof pendant in composition and texture. In general, a crude banding is present due to local concentrations of minerals. These bands vary in thickness from a few centimeters to several meters and suggest that they represent former layers of somewhat different types of calcareous sediments that were later metamorphosed to the present lime-silicate rock. The rock weathers more readily than the other members of the roof pendant and, as a whole, outcrops are not abundant. The various bands could not be correlated in the different parts of the mass because of the scanty exposures, the folding and faulting, and the frequent modification of the rock by pegmatite dikes and quartz veins. However, in general, the rock is characterized by having a mottled cinnamon-brown and light-green color, and being essentially composed of grossularite, diopside, calcite, vesuvianite, and quartz, although any of these minerals may even be absent in certain parts of the mass. The rock weathers to a dull yellowish to reddish-brown color and commonly has a rough to prominently pitted surface. Locally a white-colored rock composed largely of wollastonite is found in beds from a few centimeters to one meter in thickness.

A microscopic examination of nineteen thin sections of the rock shows that certain features are dominant. The texture varies from

fine-grained to coarse-grained, a medium-grained texture being the most common. All specimens examined showed a pronounced crystalloblastic texture.

A pale-brown, isotropic garnet showing very high relief is by far the most abundant mineral present in all the thin sections examined. The garnet characteristically occurs in anhedral masses, although in the coarser-grained facies single subhedrons or anhedrons may be present. A partial analysis of the garnet, made by Mr. H. I. Miller, gave the following results: 33.26 per cent CaO; 15.04 per cent Fe_2O_3; 0.90 per cent MgO. The specific gravity as determined by the pycnometer is 3.67. The index of refraction is 1.803 as determined by piperine-iodide melts.[8] On the basis of the above data the garnet is classified as an iron-rich grossularite.

Diopside occurs as colorless, anhedral to subhedral grains that range from 0.5 mm. to 2 mm. in length. It has a maximum extinction angle ($Z \wedge c$) of 39°, and indices of refraction of $\alpha = 1.670$, $\beta = 1.678$, $\gamma = 1.698$ (all $\pm$ 0.003).

Vesuvianite is the most erratically distributed of the principal minerals of the lime-silicate rock. It occurs in irregularly-shaped patches of anhedral grains that vary in size from a few millimeters to several centimeters in length. The mineral is very pale brown, uniaxial negative, and has low birefringence and high refraction.

Calcite intergrown with the other minerals is common, and also secondary calcite was found in all specimens examined.

Quartz occurring in anhedrons is moderately distributed throughout many of the specimens examined, and in the vicinity of the quartz veins it has penetrated the rock for considerable distances. Much of the quartz shows a late crystallization by penetrating the other minerals.

Other minerals that were observed in much smaller and irregularly distributed amounts include wollastonite, clinozoisite, hedenbergite, and sphene.

ORIGIN OF THE ROCKS COMPOSING THE ROOF PENDANT

The origin of the granite injection gneiss in this area is believed to be the same as that postulated for many similar occurrences through-

[8] H. E. Merwin, "Media of High Refraction for Refractive Index Determinations with the Microscope," *Jour. Wash. Acad. Sci.*, Vol. III (1913), pp. 35–40.

out the Front Range. Pre-Cambrian argillaceous sediments were subjected to regional metamorphism which converted the sediments to mica schist. Subsequently, the schists were injected lit-par-lit by the magma of the Silver Plume granite resulting in the formation of the present granite injection gneiss.

Three theories of origin seem possible to explain the present hornblende-plagioclase gneiss and the lime-silicate rock. The first theory assumes that the hornblende-plagioclase gneiss was formerly a basic intrusive or extrusive igneous rock. Subsequent regional and contact metamorphism changed it to a thick series of lime-silicate rock and hornblende-plagioclase gneiss. The second theory assumes that the hornblende-plagioclase gneiss was derived from an igneous intrusive or extrusive rock, while the lime-silicate rock was derived from a sedimentary rock. The third theory assumes that both the hornblende-plagioclase gneiss and the lime-silicate rock were formerly distinct sedimentary beds. The author favors the third theory.

It will be noted that the minerals present in the hornblende-plagioclase gneiss are all familiar pyrogenetic ones, and that the average mode is similar to a possible metamorphosed basic igneous rock. However, the field evidence does not indicate that this rock was formerly an igneous one since it is unlikely that the metamorphism of a basic igneous rock would result in such a thick and selective arrangement of the lime-silicate minerals on only one side of the igneous mass. No outcrop reveals any evidence of the gneiss grading into the lime-silicate beds. Also, no apophyses of the gneiss extend into the lime-silicate rock or the granite injection gneiss which might be interpreted as representing a former igneous intrusion unless the intrusion was a sill. A basic flow might explain the apparent conformable relationship between the three members of the roof pendant, providing that no prominent irregular erosion surfaces developed locally in the area now exposed.

It is believed that the hornblende-plagioclase gneiss and the lime-silicate rock can be explained more satisfactorily on the hypothesis that they were both originally distinct sedimentary beds of different compositions. The gneissic structure of the hornblende-plagioclase body and the crudely banded mineral combinations in the lime-silicate rock may have been caused by original variation in composition

of the sedimentary beds rather than as a result of great stress. Alfred Harker[9] states that in a high grade of metamorphism of a dolomitic limestone rich in foreign material (largely chloritic in composition) a rock can develop which is composed of pyroxenes, amphiboles, plagioclase feldspars, and sphene. The ratio of CaO:MgO (+FeO) is too low to permit vesuvianite, wollastonite, or garnet to form. From this information it would appear that the original sediment of the hornblende-plagioclase gneiss was probably a very impure dolomitic limestone, the impurities being chlorite or some mineral relatively high in magnesia, or magnesia and iron. The grade of metamorphism was high and was produced during the regional metamorphism that formed the pre-Cambrian schists of this part of of the Front Range. The shearing stress in a rock of this composition would be minimized during regional metamorphism because local solution and recrystallization would permit a calcareous rock to yield more readily than would an argillaceous rock under similar temperature and pressure conditions.[10] The later contact effects of the magma of the Silver Plume granite are believed to have involved little change in this rock except where there has been direct injection of felsic material, as previously stated, which has chiefly resulted in local alteration of the amphibole to a pyroxene and an introduction of quartz, orthoclase, sphene, and apatite into the rock.

The more calcic lime-silicate rock is believed to represent former sediments that ranged in composition from relatively pure limestones to very impure argillaceous and dolomitic limestones. In the case of lime-silicate rocks, the final composition and minerals formed are closely connected with the relative proportions present of lime, magnesia, alumina, and, to a less degree, iron. It has been previously indicated that part of the silica necessary to form the wollastonite in the rocks of this area was derived from hydrothermal solutions genetically related to the Silver Plume granite. The wollastonite-rich beds are believed to represent pre-existing relatively pure limestones that were first regionally metamorphosed possibly to a marble and later altered to a wollastonite-rich rock by the introduction of quartz derived from veins and pegmatite dikes genetically related to the magma of the Silver Plume granite.

[9] *Metamorphism* (London: Methuen, 1932), pp. 90–92. [10] *Ibid.*, p. 187.

The other parts of the lime-silicate rock which contain varying amounts of vesuvianite, grossularite, and diopside indicate former sediments ranging in composition from argillaceous to dolomitic limestones that were likewise first regionally metamorphosed and were later subjected to contact metamorphism by the magma of the Silver Plume granite. Minerals such as vesuvianite and grossularite that contain much lime and a moderate amount of alumina can form from the argillaceous impurities in a limestone. If alumina were present in larger quantities in proportion to calcium, the tendency would be for zoisite and anorthite to form instead of grossularite and vesuvianite. The significance of this fact is that vesuvianite and grossularite indicate a former argillaceous limestone, while zoisite and anorthite, had they been present, would have indicated a calcareous shale.

CONTAMINATED COMPLEX DIKE AT CAPE NEDDICK, MAINE

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ABSTRACT

The results of a field and petrologic study of a structurally complicated granophyre-diabase multiple dike from Cape Neddick, Maine, are presented. Although this occurrence shows many attributes of a typical composite dike, detailed evidence indicates that it is multiple in character. Reaction between granophyre magma and brecciated diabase has modified the form of the mass and produced reciprocal changes in the mineralogy. It is shown that, where such reaction has taken place, the absence of chill margins between dike components can be used as a criterion of composite intrusion only with the greatest caution.

INTRODUCTION

Cape Neddick is a small, narrow, approximately east-west trending peninsula in southwestern Maine. It projects nearly three-quarters of a mile from the mainland at a point about 14 miles north of the New Hampshire state boundary. On its south side, near a resort locality called "Dover Bluff," about 0.3 mile east of route U.S. 1A, a dike involving granophyre and diabase crops out on the shore (Fig. 1).

The size, mode of occurrence, complex structure, and contamination effects of this dike are noteworthy. They give it strong resemblance to some of the composite minor intrusions described from Mull, Arran, Ardnamurchan, and elsewhere in the British Isles. Available evidence shows that the assemblage, as a whole, has had an unusually complicated petrologic history. Further, the later stages of its evolution are illustrative of reaction between granophyre magma and diabase xenoliths.

GEOLOGIC RELATIONS

That portion of the dike which is exposed has a maximum thickness of 17 feet. When last observed (1938), 40 feet of unobstructed outcrop along the strike could be examined in detail. The dike is intruded into the Pennsylvanian (?) Kittery quartzite[1] and strikes

[1] F. S. Katz, "Stratigraphy in Southwestern Maine and Southeastern New Hampshire," *U.S. Geol. Surv. Prof. Paper 108* (1917), p. 168; A. Wandke, "Intrusive Rocks of

about N. 55° E. In common with other dikes in this area, as far as can be determined, it has an essentially vertical dip.[2] Regionally considered, it represents merely one member of a large swarm of predominantly basic multiple dikes cropping out along the coast in in this vicinity. This swarm has been transected locally by a stock-

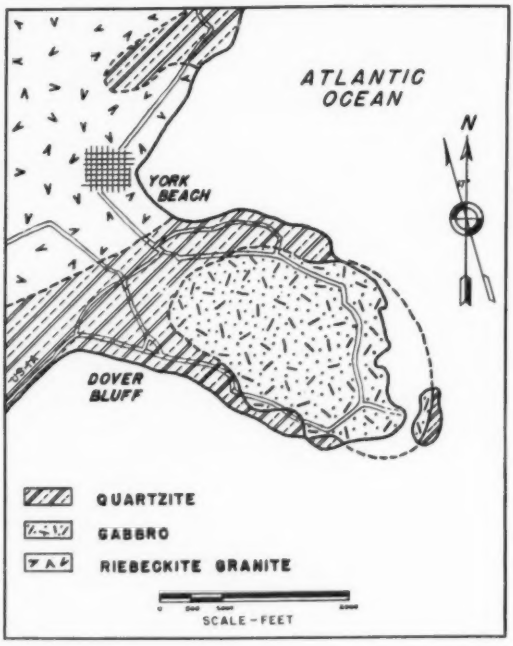

FIG. 1

like mass of Triassic (?) gabbro (Fig. 1) which forms the higher and topographically more rugged, central part of the peninsula.[3]

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the Portsmouth Basin, Maine and New Hampshire," *Amer. Jour. Sci.*, Vol. IV (5th ser., 1922), p. 142.

[2] J. C. Haff, "Multiple Dikes of Cape Neddick," *Bull. Geol. Soc. Amer.*, Vol. L (1939), p. 474.

[3] A. Wandke, "A Petrologic Study of the Cape Neddick Gabbro," *Amer. Jour. Sci.*, Vol. IV (5th ser., 1922), p. 295.

The dike consists of three structural elements involving two contrasting rock types. A mass of granophyre approximately 11 feet thick forms the central portion. Megascopically, this leucocratic rock is dense, buff colored, and shows only a few conspicuous feldspar phenocrysts. On the fresh fracture scattered blotches of iron oxide 2–3 mm. across are the only visible alteration effects. Two basic members flank this granophyre. Each consists of diabase and varies from 3 to $3\frac{1}{2}$ feet in thickness. Both are dull, greenish-black, obscurely porphyritic, massive rocks containing elongate, sparsely scattered amygdules, of which only a few are usually visible in an ordinary hand specimen. In the field, faint, irregularly spaced, but nearly parallel, flow lines can be observed in these diabasic parts, especially in portions adjacent to their contacts with the quartzite. A faint vesiculation is also visible in some of their coarser-textured phases.

The entire mass of granophyre is choked with diabase xenoliths haphazardly distributed throughout the visible exposure. All these xenoliths are structurally and mineralogically similar and in both these respects are strictly comparable to the diabase flanks. Thin sections from both flanks show that these diabasic portions are petrographically identical. Hence, it is concluded that both are parts of a previously homogeneous dike unit.

Although many of the xenoliths range in size from about 1×1 to 4×8 inches in cross section, some of the larger exceed 2 or more feet in longest dimension (Fig. 2). Regardless of size, they are irregular in form and often exhibit rounded outlines with conspicuous marginal embayments. Few are noticeably circular or oval. Many of the fragments an inch or less across are quite inconspicuous, for they are so dismembered by granophyre as to be merely attenuated relics. Such small xenoliths are a pale-buff hue throughout and especially so on their margins. For this reason they often blend most effectively with the light-colored host. Larger inclusions, which have not undergone such relatively complete modification, are penetrated and sometimes transected by slender apophyses and filaments of granophyre.

Careful field examination shows that there is no suggestive juxtaposition or continuation across intervening matrix areas either of

flow lines or of vesicular bands in adjacent xenoliths. Moreover, adjacent xenoliths are so very irregular in outline that they cannot be correlated on this basis. As will be shown, this disparity in form and outline in particular is believed to have resulted from marginal encroachment.

FIG. 2

CONTACT FEATURES

The exterior of each diabasic member chills abruptly at its junctions with the quartzite. On the other hand, both contacts of the inclusion-choked granophyre with massive flanking diabase are transitional rather than sharply defined. No appreciable progressive reduction in grain size can be detected in granophyre at these contacts. In place of definite chill margins, gray or greenish-brown contact zones, usually about $\frac{1}{4}$–$\frac{1}{2}$ inch in width, are developed. Thus the chill selvages expectable between multiple dike components are replaced by narrow transition zones. The absence of chill between members of contrasting lithology in dikes of this general type has been used as a criterion of composite intrusion, to which class this complex could be definitely assigned were it not for other features. The contacts between granophyre and xenoliths are also gradational and zonary in character on the entire periphery of each fragment.

Although this lack of chill prevents direct, independently conclusive determination of the relative ages of granophyre and diabase, other evidence throws light on the order of succession. First, the

similarity of the xenoliths to one another and to the flanking members strongly supports belief in their derivation from the latter. Second, the texture of both flanking diabasic members becomes coarser as granophyre is approached. This increase in grain size toward the interior of the complex is perfectly symmetrical. Such gradation, taken together with the structural and mineralogical identity of the xenoliths and diabasic flanks, would appear to establish definitely that the granophyre is the younger of the two.

CLASSIFICATION OF THE INTRUSION

The bilateral symmetry of this dike, together with the central position of the granophyre, is typical of many composite intrusions showing analogous lithologic association. However, both composite and multiple dikes may show a bilaterally symmetrical arrangement of components according to the formula ABA, taking only the simplest forms possible. Discrimination between the two types—composite and multiple—may sometimes be difficult. Their differentiation frequently involves judgment of several factors other than simple distribution of rock types within the intrusion. The presence or absence of interior chill zones, textural and mineralogical contrast and gradation, and estimation of the relative time intervals between intrusion of members must often be considered. Bilaterally symmetrical dikes consisting of basic flanking members separated by a central acid participant are the only types requiring discussion in this instance. Such dikes—the simplest from the structural point of view—may be subdivided a priori into four principal types:

A. *Dikes differentiated in situ* may be recognized by the lithologic gradation from basic to acid from the margins toward the center, the absence of chill of any lithologic phase or portion thereof against any part of the interior of the mass, and textural gradations which may vary sympathetically with the lithologic gradation.

B. *Composite dikes* are formed by intrusion of basic magma followed after only a short interval by intrusion of acid magma into the central part of the still, at least partially, liquid basic material. In recorded occurrences of this type felsite, quartz-porphyry, granophyre, and bostonite often comprise the central member; basalt or diabase the flanks. As with dikes differentiated *in situ*, no internal chill of acid component against basic flanks is evident. As distinguished from Type A, there is no systematic lithologic gradation but conspicuous contrast in composition between components.

C. *Symmetrical multiple dikes* are produced by intrusion of acid magma into a completely consolidated basic dike. No lithologic gradation is here expectable either, but the acid portion definitely chills against the basic flanks. In many occurrences the lithologic associations are comparable to those of Type B. Although the absolute time interval between intrusions cannot be fixed, the chilling of the acid rock against the basic flanks distinguishes such occurrences from those of Type B. There seems to be no reason why such dikes cannot be produced by activity related to distinctly different intrusive epochs, perhaps widely separated in time.

The basic dike rock in such multiple intrusions is completely consolidated at the time of the second invasion, and the acid portion may be introduced along any plane within the earlier mass. In Type B the central, still-liquid zone serves naturally as the passageway for later acid magma. Thus, symmetrical distribution of components is not necessarily an inherent feature of Type C as it is in Types B and A.

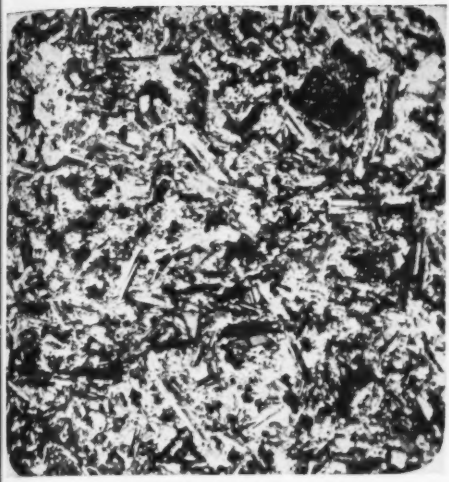
D. In this type of multiple-dike bilateral symmetry (ABA) is produced by intrusion of an acid dike between two basic ones. Both the latter are fully consolidated, contiguous, and in multiple relation prior to intrusion of the third member. Each of the three members shows well-defined chill selvages. In this type, as in C, symmetry, if present, is fortuitous. When developed it is consequent only upon the approximately equal thickness of earlier members.

As regards classification of the Cape Neddick intrusion, it is readily seen that it possesses characteristics of both Type B and Type C. There is marked contrast in composition of the rocks involved. It lacks the interior chill of the central acid member against basic flanks, an attribute of Type B. On the other hand, the presence of holocrystalline xenoliths derived from adjacent flanks and the textural gradation in these flanks indicate a definite hiatus such as is typical of Type C. The complex is considered by the writer as belonging genetically to Type C, but as one lacking interior chill because of reaction between granophyre and diabase. It is thus a modified type which would be readily assigned to Type B were it not for the unequivocal evidence indicating a relatively long lapse of time between successive intrusions.

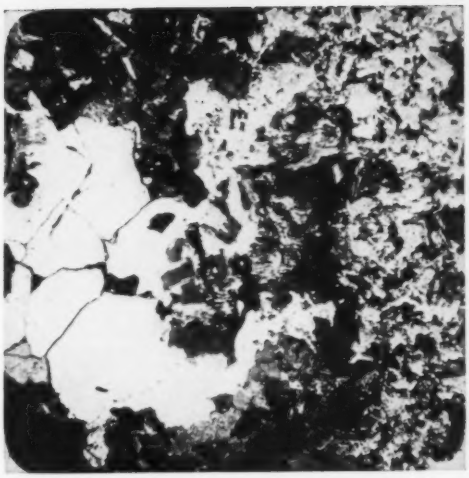
PETROGRAPHY

DIABASE

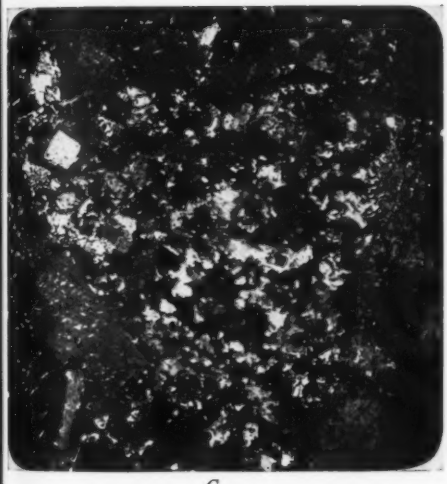
Microscopically the diabase is a medium-textured (0.5 mm.) porphyritic rock containing phenocrysts of pyroxene and plagioclase in a groundmass which originally consisted of pyroxene and labradorite (Fig. 3, *A*). Nearly all the orthotectic pyroxene (augite?) is altered



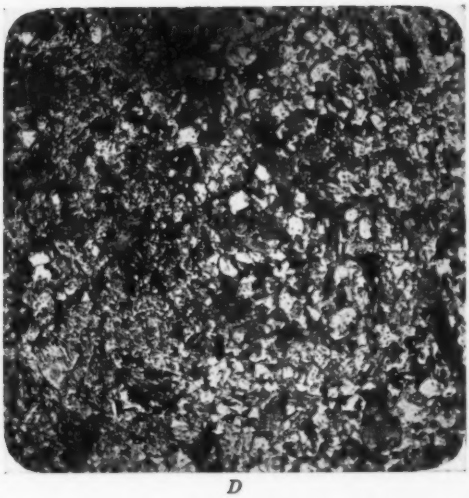
A



B



C



D

FIG. 3.—(*A*) Photomicrograph showing the structure of the diabase formed of an interlocking plexus of plagioclase laths and interstitial pyroxene now uralitized. Water-clear quartz grains dispersed throughout are clearly discernible (crossed nicols, mag. 30×). (*B*) Photomicrograph showing a portion of a rather large quartz-filled vesicle in diabase. Around its margins have been introduced extremely fine-grained micropegmatite intergrowths which, in part, replaced basic plagioclase in portions of the diabase contiguous to the vesicle (crossed nicols, mag. 45×). (*C*) Photomicrograph showing structure of typical granophyre. The confused aggregate character of the groundmass and the exceedingly fine texture of the micrographic intergrowths are well shown. At lower right is an albitized orthoclase phenocryst, twinned on the Carlsbad law and embayed by fringing micropegmatite (crossed nicols, mag. 30×). (*D*) Photomicrograph of a section across the contact of granophyre and a diabase fragment. Biotitized diabase at left. The persistence of quartz, in grains of considerable size and within the contact zone, is evident. With the quartz are abundant shreds of bluish-green hornblende such as is everywhere common in the contact zone.

to matted aggregates of pale greenish-brown, fibrous hornblende. This modified condition makes it impossible to determine accurately the optical constants of the principal mafic constituent. The plagioclase phenocrysts ($Ab_{45}An_{55}$) are, on the other hand, only slightly altered and carry mere traces of carbonate and a few sericite flakes. The groundmass plagioclase ($Ab_{55}An_{45}$) is apparently somewhat more sodic than the phenocrysts. Possibly occasional olivine phenocrysts were present originally but, if so, they are now represented only by local concentrations of granular magnetite.

The well-preserved groundmass structure is a typically diabasic one in which plagioclase laths form a meshwork whose interstices were filled with pyroxene. Only rarely are extremely fine granules and small, residual cores of this latter mineral detectable at present. Minute grains of accessory apatite, magnetite, and an occasional titanite crystal also occur.

Scattered throughout the groundmass in some thin sections are minute flakes and scales of highly absorptive red-brown biotite associated with fine granular magnetite. The fibrous secondary hornblende already mentioned is widely distributed, is generally more abundant than biotite, and sometimes intergrown with it. Quartz occurs as small interstitial grains, which may occasionally attain the dimensions of small xenocrysts. It is also present as an associated mineral in interstitial micropegmatite intergrowths. Here and there are secondary aggregates of square or rectangular outline consisting of matted hornblende, magnetite, chlorite, epidote, and carbonate, which presumably are pseudomorphs after the pyroxene phenocrysts.

Though structurally massive, the rock is slightly amygdaloidal in the coarser-textured portions. The amygdules, which are 2–5 mm. across, contain rather coarsely crystalline (0.5–1.0 mm.) aggregates of quartz and calcite with occasional hornblende fibers and pyrite grains. In some of the cavities exceedingly fine-textured, plumose micropegmatite is developed between the quartz-calcite aggregates and the vesicle walls. These intergrowths sometimes replace the material in the amygdules themselves and, locally, portions of the groundmass contiguous to the latter (Fig. 3, *B*). In such cases the groundmass feldspar is most often replaced by micropegmatite.

Such a condition might be construed as resulting from deuteric action but in this instance is believed to have been produced by reaction during intrusion of granophyre.

GRANOPHYRE

This is a medium-textured (0.2–0.5 mm.) rock carrying conspicuous oligoclase ($Ab_{85}An_{15}$) and orthoclase phenocrysts averaging 2 mm. in length in a groundmass of albite, orthoclase, quartz, and some oligoclase (Fig. 3, *C*). The accessory minerals include magnetite, apatite prisms, titanite, zircon, and muscovite. There are also grains of epidote, carbonate, rutile, limonitized pyrite, and a few chlorite flakes scattered throughout the rock.

Biotite and possibly a very few hornblende phenocrysts were present originally. Now, however, mafic phenocrysts are represented only by fine, granular, complex aggregates of epidote, chlorite, calcite, magnetite, rutile, and leucoxene. The derivation of these aggregates is believed to be from biotite for the most part. However, this can be inferred only from the presence of rectangular areas containing apatite euhedra and zircon grains with pleochroic halos preserved in matted chlorite. The distribution of these euhedral accessory minerals strongly suggests original biotite phenocrysts poikilitic with respect to them. The development of chlorite in parallel interdigitating tongues also suggests replacement along biotite cleavages. In any case the ferromagnesian phenocrysts appear to have been only sparsely developed originally.

The microstructure of the groundmass is intricate and its general hypidiomorphic granular development much subdued by micropegmatite. These exceedingly fine-textured quartz-albite intergrowths are so abundant that only in rare patches can the fundamental nature of the groundmass be detected. In places its interlocking structure is destroyed by enveloping micropegmatite. Where such effects are most intensive, the granularity is to all intents completely superseded. Where incomplete, a fabric physically resembling sieve structure, such as may be developed in diablastic metamorphic rocks, may be produced.

The micropegmatite shows great variation in distribution and structural habit. Most commonly it is intimately mixed with

groundmass feldspars. Other masses fringe the feldspar phenocrysts. The quartzo-feldspathic components of such selvages, like the groundmass micropegmatite, usually show optical continuity over considerable areas. Sometimes they are optically continuous with contiguous groundmass patches. Some phenocrysts are deeply embayed by extensions from such fringing micropegmatite. In such cases polysynthetic twinning in the plagioclase is generally vague and in some places obliterated. However, feldspar remnants, in optical continuity with one another and with unreplaced portions of the host, often persist within the graphic selvages and establish the identity and earlier continuity of such modified phenocrysts.

THE PROBLEM OF ENCROACHMENT

FIELD EVIDENCE

The absolute extent of marginal encroachment upon, and modification of, the xenoliths by granophyre cannot be determined, for it is impossible even to estimate the original volume of brecciated material. Nevertheless, if preliminary fragmentation be conceded, an earlier development of relatively angular fragments seems expectable. At present, however, rounded xenoliths and the abundant granophyre apophyses and embayments in them are very conspicuous. In some instances these cross-cutting veinlets are so numerous as to indicate virtual dismemberment of the fragments. Since the source diabase is homogeneous and structurally isotropic, it is difficult to account for these penetrating and anastomosing veinlets, which follow no apparent pattern, unless some replacement has ensued.

Some of the larger xenoliths are completely transected by thin granophyre stringers. Perhaps these have filled fractures developed during brecciation, for there may well have been some initial control of them by incipient crushing. However, they are wavy and discontinuous in behavior, vary unpredictably in thickness, and are distributed without regard to any visible structure within the fragments. Careful examination shows that flow lines and vesicular bands in once-continuous xenoliths show no displacement on opposite sides of the veinlets. Relatively intensive fragmentation alone, therefore, cannot be invoked to explain their irregular arrangement.

It thus appears probable that encroachment by granophyre has produced some pseudobrecciation. This statement is not a refutation of the fact that the interior of the diabase was earlier brecciated. But the ramifying granophyre veinlets and the continuity of structures across them in some of the larger xenoliths suggest that another process of dismemberment, independent of deformation, has been operative.

Other indirect evidence substantiating encroachment is available. Granted that the diabase was brecciated by post-consolidation movements, then it is difficult to conceive how such action would produce the relatively even internal contacts between granophyre and flanking diabase. In the light of the evidence showing encroachment on xenoliths the approach to parallelism of these contacts may be interpreted as resulting, in part at least, from the same process. If encroachment upon xenoliths be considered satisfactorily demonstrated, then such action cannot logically be restricted to them alone. This question of encroachment along contacts must, however, remain largely a matter of interpretation and degree, for it is possible that the xenoliths surged into position and that at the level in the dike now exposed there was clean fracture.

The essential parallelism of the granophyre with respect to the diabase flanks is notable. It is a condition which suggests that the brecciating movements were consonant in direction with those producing the fissure into which the earlier diabase was intruded. Such concordance might be interpreted to signify that both periods of deformation were very likely manifestations of one intrusive epoch. If so, a relatively small time lapse between intrusion of diabase and granophyre would be expectable. This suggestion of a relatively short hiatus has bearing on the availability of two chemically contrasting magmas.

MICROSCOPIC EVIDENCE

The microscopic relations in contact zones are most significant as regards the question of reaction and encroachment. Granophyre one or more feet from any diabase would, it is believed, ordinarily exhibit typical granularity. Microscopically, it is plain that at contacts of granophyre both with xenoliths and with flanks the grain size of the former shows no sensible diminution as compared with

more remote portions. As far as can be determined, the texture in these contact zones is comparable to that in granophyre remote from diabase. Within 3 mm. of contacts stout feldspar phenocrysts occur in granophyre. They are similar in habit, dimensions, and composition to those found elsewhere in this rock. The constituents of the groundmass of the acid rock likewise show no recognizable size reduction controlled by proximity to contacts. Unfortunately, micrometric measurement of the texture of the granophyre at and near contacts is impossible because of the graphic structure.

The contacts can be most accurately defined under the microscope. The abundance of hornblende and biotite in the diabase affords a sharp color distinction as compared with the light-colored granophyre. Further, there is conspicuous structural contrast between the two rocks for both retain their distinctive fabric up to their actual junctions.

Despite the facility with which the two can be distinguished there is evidence of reaction. In diabase, patches of micropegmatite occur a few millimeters from the limits of distinctive granophyre and in greater quantity than in more remote areas. In some places deposition of micropegmatite has greatly obscured the diabasic structure adjacent to contacts and has proceeded with intensive albitization of labradorite. Indeed, the groundmass plagioclase in diabase close to contacts is generally albitized, irrespective of its proximity to introduced micropegmatite.

No fractured, shattered crystals or other deformation phenomena, such as might be produced by brecciation of diabase, are visible at contacts with granophyre. On the contrary, there is interpenetration of the two rock structures. Plagioclase grains, continuous with the diabase mesostasis, project into granophyre for short distances. Tabular biotite crystals are very abundant in diabase near contacts. Many such grains, structurally continuous with diabase, have a characteristic deep-brown color in the former but are modified to hornblende where extending into granophyre. Some of these modified grains, lying in granophyre 2–3 mm. from any contact, have pale-brown cores. Strongly pleochroic, blue-green hornblende, which is believed to be a recrystallized variety of the uralitic secondary amphibole so common in the diabase, is concentrated in the acid rock within a few millimeters of contacts, rapidly diminishes in

amount with distance therefrom, and is absent 5–6 mm. away (Fig. 3, *D*). Some of these fibrous hornblende aggregates are now completely isolated and form outliers in the granophyre. The only dark mineral found in granophyre remote from contacts is chlorite as pseudomorphs after biotite.

Such evidence suggests that intrusion of the granophyre was accompanied by appreciable reaction. The major changes thus produced in the diabase, and with reasonable certainty ascribed to this process, are: (1) introduction of micropegmatite, (2) albitization of groundmass plagioclase, (3) the formation of abundant brown biotite near contacts.

Several types of structural and mineralogical evidence suggestive of contamination in composite minor intrusions have been recorded. Much of this is obviously diagnostic only when suggestive data are found in combination. In the following are presented the more salient features specifically cited as supporting the hypothesis of contamination in such occurrences. The material included was derived from selected sources which were, in whole or in part, important detailed studies of contaminated minor intrusions.[4] Choice of the features selected was rigorously restricted to those reported typical of composite intrusions of the type ABA. Such dikes should therefore show attributes closely analogous to the one here described.

FEATURES SUGGESTIVE OF REACTION AND CONTAMINATION IN COMPOSITE MINOR INTRUSIONS

MEGASCOPIC AND FIELD EVIDENCE

1. Reaction rims or corrosion zones around basic xenoliths in acid rock. Also "corroded" condition of contacts between acid and basic members.

[4] A. Harker, "Tertiary Igneous Rocks of Skye," *Mem. Geol. Surv. United Kingdom* (1904), pp. 200, 202, 204, 209, 218; N. L. Bowen, "Behavior of Inclusions in Igneous Magmas," *Jour. Geol.*, Vol. XXX (1922), p. 528; E. B. Bailey *et al.*, "Tertiary and Post-Tertiary Geology of Mull, Loch Aline, and Oban," *Mem. Geol. Surv. Scotland* (1924), pp. 197, 354–56; J. E. Richey *et al.*, "Geology of Ardnamurchan, Northwest Mull and Coll.," *Mem. Geol. Surv. Scotland* (1930), pp. 62–63, 100, 197–99; G. W. Tyrrell, "Geology of Arran," *Mem. Geol. Surv. Scotland* (1928), pp. 136–37, 146–47, 196–97, 355; S. I. Tomkieff and C. E. Marshall, "The Mourne Dike Swarm," *Quart. Jour. Geol. Soc. London*, Vol. XCI (1935), p. 274. For more general treatment see also F. F. Grout, "Criteria of Origin of Inclusions in Plutonic Rocks," *Bull. Geol. Soc. Amer.*, Vol. XLVIII (1937), pp. 1534–35; and S. Powers, "Origin of the Inclusions in Dikes," *Jour. Geol.*, Vol. XXIII (1915), pp. 1–10, 166–82.

2. Cross-cutting and anastomosing veinlets of acid dike material in basic members or xenoliths derived from them.

3. Absence of chill selvages in acid rock at contacts with basic members.

4. Strewing-about of xenocrysts. Presumably in some cases this may indicate dismemberment of xenoliths.

5. Abundance of round basic xenoliths in those parts of the acid member adjacent to contacts with basic members.

6. Increase in number of basic xenoliths in acid member with approach to contact with basic members.

7. Sympathetic change in grain size of basic xenoliths in acid rock as contact of the latter with basic member is approached. This textural gradation is a very strong indication that the brecciated rock cooled normally and that the xenoliths were derived from the contiguous mass. Such relations indicate the source of the xenoliths, the nature of the basic material originally can be compared with modified xenoliths, and reaction effects can be closely evaluated.

MICROSCOPIC EVIDENCE

I. Mineralogical

A. In acid component (commonly quartz-porphyry, granophyre, bostonite, felsophyre)

1. Crystallization of hypidiomorphic rhombic pyroxene and/or augite following incorporation of basic xenoliths
2. Presence of relatively basic plagioclase xenocrysts
3. Relative abundance of iron "ore" near contacts with basic xenoliths
4. Unusual abundance of biotite and interstitial quartz, especially in vicinity of contacts with basic members

B. In basic component (commonly basalt, dolerite, diabase) or fragments thereof

1. Presence of interstitial, xenocrystic, or micrographic quartz in unusual amounts
2. Abundance of interstitial or xenocrystic orthoclase and sodic plagioclase near contacts with acid member
3. Albitization, or more general acidification, of orthotectic, calcic plagioclase
4. Widely dispersed patches of micropegmatite
5. Chloritization of original ferromagnesian minerals
6. Pseudomorphs of biotite after augite, and of rhombic pyroxene after olivine

NOTE.—The presence of introduced substances, supposedly derived from the acid member, or of alteration products after primary essential minerals is more suggestive when such modification effects increase or become progressively intensified with proximity to the acid member.

II. Microstructural features
  A. In acid component
    1. Shattering of xenocrysts, as of labradorite for example
    2. Absence of micrographic intergrowths in zones peripheral to basic xenoliths
    3. Preservation of salitic structure in augite xenocrysts
  B. In basic components or fragments thereof
    1. Destruction of original ophitic structure
    2. Clear borders of alkali-feldspar about xenocrysts of same composition internally congested with inclusions. Presumably suggestive of introduction and renewed growth
    3. Disseminated "skeletal" iron ore
    4. Fringing growths of albite about primary calcic plagioclase
  C. Common to both acid and basic components
    1. Rapid changes in composition near contacts and absence of chill between members

Comparison with this outline shows that the Cape Neddick dike possesses many points of similarity with other occurrences exhibiting reaction effects. The abundance of rounded, embayed xenoliths and of cross-cutting, anastomosing granophyre veinlets in them, as well as the lack of chill selvages in the acid rock, are suggestive field characteristics. The presence in granophyre at contacts of ragged shreds of blue-green hornblende, both as grains integral with diabase and as definite outliers, is believed to indicate a suggestive modification. There appears to have been notable change in the properties of this hornblende, which, as far as can be determined, is indigenous to the diabase in this complex. The abundance of biotite in the diabase fragments as compared with the mere sprinkling of such mica in the flanking portions and the extreme congestion of this mineral in contact zones also suggest control by reaction. Further, the development of micropegmatite, albitized plagioclase, and occasionally quartz xenocrysts in diabase also seem indicative of modification resulting from attack by granophyre magma.

These mineralogical changes are not, perhaps, either so intensive or so extensive as some of those stated to have ensued elsewhere in analogous occurrences. Only relatively small portions of the granophyre, i.e., narrow zones adjacent to contacts with diabase flanks and xenoliths, show effects which can with reasonable certainty be ascribed to reaction. In the diabase, on the other hand, and especial-

ly in the xenoliths, there is a relatively greater variety and intensity of effects and a more general distribution of products derived by reciprocal change.

Modification of orthotectic pyroxene in this diabase to fibrous greenish-brown, uralitic hornblende can be readily demonstrated in thin section. Such an alteration is not, however, common in other basic dikes of the region and in this instance may possibly in large part result from reaction. On the other hand, the extent of biotitization in the diabase for which the granophyre alone can be held responsible is an even more difficult problem. The contact of the dike here discussed with the gabbro is not exposed. But at many places in the adjacent area shatter breccias containing basic dike fragments are found in the gabbro at and near its junction with the country rock. It can be safely concluded from the field evidence in the surrounding area that this dike also attained full development before intrusion of the gabbro.

Brown biotite is by far the most widespread secondary mineral in the basic dikes of the region.[5] It invariably occurs most abundantly in those parts of the dikes closest to gabbro. In consideration of its almost universal distribution in such proximity to this intrusive, it is interpreted as a contact product resulting from attack by the acid border phases of the gabbro magma. Hence it is probable that not all the biotite in the diabasic portions of this particular dike can be construed as resulting from reaction with granophyre. It has proved impossible to differentiate microscopically between the exceedingly minute biotite individuals developed by contact action of gabbro and that produced by reaction with granophyre in the dike here discussed. But there is unquestionably more biotite in the xenoliths themselves than in the flanks. Furthermore, this mineral is most abundant on the peripheries of the xenoliths and in those parts of the flanks contiguous to granophyre. Its distribution, so concentrated with respect to contacts, is interpreted as indicating that much of it may thus be a pregabbro reaction product developed during intrusion of the granophyre.

Albitization of basic plagioclase, the presence of sporadic quartz xenocrysts, and the dissemination of micropegmatite in the basic

[5] Haff, *op. cit.*, p. 508.

flanks and xenoliths indicate an acidification of diabase and would seem to substantiate the introduction of potassium, sodium, and silica from the granophyre. The granophyre has undergone more limited complementary changes in composition, but both hornblende and biotite now occur in this rock in the vicinity of contacts. The presence of these substances is believed to be quite compatible with the physicochemical conditions which can be presumed to have prevailed during immersion of the basic fragments in the acid magma. It should be noted that most, if not all, the mafic phenocrysts in the granophyre were originally biotite. Bowen[6] has demonstrated that, under the conditions postulated, the granophyre magma would have been effectively supersaturated for all members of the discontinuous reaction series earlier than biotite. It is this latter mineral which is most abundantly developed at and near contacts. Its occurrence there is wholly in agreement with the evidence that biotite was the phenocrystic mafic crystallizing from the granophyre magma at the time of its intrusion. The hornblende grains present in granophyre near its margin are interpreted as unstable relics, and it is not impossible that much of the biotite was derived by the reconstitution of this mineral.

CONCLUDING REMARKS

The close association of basalt and diabase with felsophyre, quartz-porphyry, bostonite, and granophyre in contaminated composite minor intrusions has often been commented upon. So persistent was this relationship in Skye that Harker[7] intimated that it, together with prevailing field relations, strongly suggested intrusion of different members separated by an extremely short hiatus. Somewhat later, Thomas reinforced this opinion. In a general discussion of composite intrusions on Skye, Mull, and Arran, the latter notes that in most cases the central acid members habitually lack chill against the basic flanks but merge very gradually with them. He inferred that, at least in such cases as there encountered, the lack of chill selvages indicated essential contemporaneity of two chemically contrasting magmas. He states:

> Judging by the form and relations of the rocks involved, however, there appears to be no reasonable doubt of the simultaneous availability of two com-

[6] *Op. cit.*, p. 533.

[7] *Op. cit.*, p. 169.

positionally different magmas and of their coexistence in the same magma-reservoir, one magma following upon the other along the same fissure after a very short interval of time, before the first had an opportunity to solidify completely.[8]

He suggests a replacement of at least partially liquid basic material by later acid magma, summarizing as follows:

It thus appears that, generally, the fissure was first filled by a basic magma that partially solidified, and that this was followed by a magma of different composition, the latter usually occupying the center of the sill or dyke. The more acid magma presumably replaced all the basic magma that had not previously solidified and resorbed as much of the solid as its superfluous heat would allow.[9]

In the dike here described the character of the diabase and xenoliths thereof is highly suggestive as regards the relative length of the time interval between intrusions. First, the xenoliths are of the same structure and composition as contiguous portions of the diabase flanks. Second, their texture is relatively coarse and of such magnitude as would be expectably developed in the center of the parent-diabase. Third, symmetrical textural gradation in the flanking members toward the interior is found. Fourth, consolidation appears to have been sufficiently advanced so that typical diabasic structure was developed in the entire mass now visible. Fifth, in order to have undergone brecciation the central part of the diabase must have been structurally rigid. These facts are interpreted as indicating conclusively that sufficient time for complete consolidation of the diabase elapsed before intrusion of granophyre.

Were the xenoliths not present, the lack of chill in this dike might readily be interpreted to signify essential contemporaneity of diabase and granophyre. But the evidence shows that the chill which presumably would have developed has been either deterred from forming or been destroyed by reaction. Thus, the facts show that the absence of chill selvages must, at least in certain instances, be interpreted with caution. It would appear that the lack of them in some composite dikes and sills need not necessarily be ascribed to successive intrusions closely spaced in time. It is possible that in some other instances, where brecciation has not intervened so conspicuously, lack of chill may also have resulted from reaction of acid

[8] Richey *et al.*, *op. cit.*, p. 63. [9] *Ibid.*

magma with basic flanks, especially where an earlier dike has been reopened along a clean fracture. In any case it would appear that interpretation of the relative time intervals between the intrusion of contrasting members of some composite dikes must be made with circumspection, especially where there is evidence of reaction between them.

SUMMARY

The evidence indicates that a completely consolidated diabase dike was deformed with the development of a breccia in its central portion. The breccia zone was then occupied by a later intrusion of granophyre magma. This combination of events produced a dike, in the middle of which is a xenolith-congested granophyre. Accompanying the intrusion of granophyre, reaction between the xenoliths, diabase flanks, and the acid magma took place. Attack by granophyre appreciably modified both the form and the composition of the inclusions and flanks. Dismemberment of the inclusions by granophyre apophyses and veinlets produced a pseudo-brecciation of some fragments. Hence there have been two periods of fragmentation, the earlier mechanical, the later resulting from attack by granophyre.

Reaction between diabase and granophyre magma produced reciprocal changes in the mineralogy of the two rocks. Chief among these was the albitization of calcic plagioclase, the development of xenocrystic quartz and of micropegmatite, and the formation of abundant brown mica in diabase. Reaction is believed to have hindered formation of, or obliterated chill margins in, the granophyre. Whereas in the absence of the xenoliths, this dike would be classified as a composite intrusion, the detailed evidence indicates a relatively long time interval between intrusion of the two magmas and proves its multiple character.

AMERICAN DOCTORATES IN GEOLOGY, 1931–40

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ABSTRACT

An attempt has been made to collect information covering all doctorates in geology granted by American universities during the decade 1931–40. Tables have been prepared to present facts obtained.

There are available published lists of doctorates granted by American universities during the past decade.[1] Names of the recipients of the Doctor's degree in geology, universities granting the degree, and thesis titles are listed. In the published bulletins the doctorates in geology are separated into several groups: geography (several theses in geomorphology are so listed), geology, mineralogy, paleontology, and seismology. An attempt has been made by the writer to gather from each department of geology granting a Doctor's degree further pertinent data in the belief that an impartial presentation of the information is of value to teachers and students contemplating work leading to the doctorate. A similar but less detailed study of all American doctorates in geology granted prior to 1931 was prepared by C. K. Wentworth.[2]

Unfortunately, in a tabulation of this type, the desired completeness cannot be attained. Many departments have been unable to furnish all the information. However, in most instances enough data have been obtained to indicate general trends. Unintentional oversights and discrepancies may appear. The writer hopes that these are at a minimum. All information used for the decade 1931–40 has been obtained directly from the departments concerned.[3]

[1] *Nat. Res. Coun. Bull.* ("Reprint and Circular Series," Nos. 101 [1931], 104 [1932], and 105 [1933]); National Research Council, American Council of Learned Societies, and the Association of Research Libraries, *Doctoral Dissertations Accepted by American Universities*, Nos. 1 (1934), 2 (1935), and 3 (1936); Association of Research Libraries, *Doctoral Dissertations Accepted by American Universities*, Nos. 4 (1937), 5 (1938), 6 (1939), and 7 (1940).

[2] "American Doctorates in Geology," *Jour. Geol.*, Vol. XLI (1933), pp. 432–38.

[3] In several instances material received directly from the departments of geology granting degrees does not agree with published records. In such cases, information furnished by the departments has been used.

Up to the year 1931 some 41 schools had granted 768 doctorates in geology.[4] Each succeeding decade has witnessed a greatly increased number of degrees. Between 1921 and 1930, 390 degrees were granted.[5] Between 1931 and 1940 there was an increase of 70 per cent, with a total of 671 degrees granted by 45 universities (Table 1). Thus, in the past decade more than 46 per cent of all doctorates in geology given by American universities have been granted, or, in other words, the doctorates in geology given in the past decade amount to 86 per cent of all those previously granted. The year 1935 marked the all-time high for degrees granted in a single year, for 84 doctorates were granted by 26 departments in the various fields of geology.

Twenty-two doctorates have been awarded to women (Table 1). This is 3 per cent of the total for the decade. It may represent several times the total number of degrees previously awarded to women in the field of geology.

Six universities granting the doctorate in geology before 1931[6] have dropped from the list for the past decade. Brown, Fordham, Pittsburgh, Syracuse, Vanderbilt, and Washington and Lee conferred no doctorates in geology since 1930. Some departments have indicated that they are no longer offering work leading to the Doctor's degree in geology but are concentrating on schedules designed to fulfil the requirements for the Master's degree only. In the list of schools granting the doctorate in geology since 1930 (Table 2), thirteen new names appear: Arizona, Catholic University of America, Clark University, Colorado School of Mines, Louisiana State University, Northwestern University, University of Oklahoma, Rochester University, Rutgers University, St. Louis University, University of Southern California, University of Texas, and Washington University (St. Louis).

Table 2 lists by universities the total number of doctorates in geology granted prior to 1931, the number during the decade 1931–40, and the total number granted by the various schools. Examina-

[4] Wentworth lists only 40 schools and 764 degrees. His list, however, does not include Brown University, which granted four doctorates in geology before 1931: two in 1916, one in 1917, and one in 1920.

[5] Wentworth, *op. cit.*, p. 435.

[6] *Ibid.*, p. 437.

TABLE 1

DOCTORATES IN GEOLOGY, 1931–40

School	31	32	33	34	35	36	37	38	39	40	Total
Arizona	1	....	....	....	1	1	1	2	1	2	9
Bryn Mawr	(1)*	(1)	....	....	....	....	....	(1)	....	....	3
California	2(1)	3	3	4	3	2	....	4	3	5	30
California Institute of Technology	3	2	5	5	4	3	6	1	2	2	33
Catholic University of America	....	....	....	....	....	....	1	....	....	....	1
Chicago	1	5	3	4	12	3	5(1)	7	4	6(1)	52
Cincinnati	....	....	1	....	1	....	1	1	1	....	5
Clark	....	....	....	....	....	....	....	1	1	....	2
Colorado	....	....	1	1	....	2	....	3	....	2	9
Colorado School of Mines	1	2	3	2	....	....	....	1	....	3	12
Columbia	1	3	1	1	5	4	6	8	6	3	38
Cornell	3	1	8	1	5	1	1(1)	3	1	1	26
George Washington	....	1	2	....	....	....	....	....	....	....	3
Harvard†	5	5	6	6	9	14	4	8	8	5	70
Illinois	2	1	2	1	1	1	2	....	1	1	12
Indiana	....	1	3	1	....	1	....	....	....	....	6
Iowa	3(1)	3	2	4	5	....	2	5	....	5(1)	31
Johns Hopkins	1	2	4(1)	3	3	3	2	1	3	1	24
Kansas	1	....	....	1	....	1	....	....	1	....	4
Louisiana State	....	....	....	....	....	....	1	3	1	1	6
McGill	....	....	3	3	2	1	2	1	2	4	18
Massachusetts Institute of Technology	....	....	2(1)	2	2	....	4	3	4(1)	6	25
Michigan	2	1	5(1)	....	2(1)	3	1	2(1)	3	1	23
Minnesota	3	3	3	7	2	1	8	1	2	2	32
Missouri	1	2	1	1	1	....	....	....	1	2	9
New York University	....	2	1	....	2	....	....	(1)	....	2	8
North Carolina	1	....	(1)	....	....	....	....	....	3	1	6
Northwestern	....	1	2	....	1	1	....	....	(1)	....	6
Ohio State	....	....	1	....	....	1	2	1	1	1	7
Oklahoma	....	....	....	....	1	....	1	....	....	....	2
Oregon	....	1	....	....	....	....	....	....	....	....	1
Pennsylvania	....	....	....	....	1	....	....	....	1	....	2
Princeton	6	4	4	1	7	8	3	4	4	5	46
Radcliffe	....	(1)	....	....	....	....	....	....	....	(1)	2
Rochester	....	....	....	....	....	....	1	....	....	....	1
Rutgers	....	....	....	....	....	....	....	(1)	....	....	1
St. Louis	....	1	....	1	1	....	....	....	1	....	4
Southern California	....	....	....	....	....	1	....	1	....	....	2
Stanford	....	1	3	2	2	3	2	1	1	1	16
Texas	1	....	....	1	....	....	(1)	....	....	....	3
Toronto	1	1	1	6	5	2	2	1	1	3	23
Washington (St. Louis)	....	....	....	....	....	2	....	2	....	....	4
Washington (Seattle)	....	....	....	....	....	1	1	....	....	....	2
Wisconsin	5	3	4	3	3	3	....	2	1	1	25
Yale	2	2	1	1	2	7	1	1	6	4	27
Total by years	49	53	79	62	84	70	63	72	66	73	.....
Total for decade	....	....	....	....	....	....	....	....	....	....	671

* Figures in parentheses are women doctorates. † Includes department of mining engineering.

TABLE 2

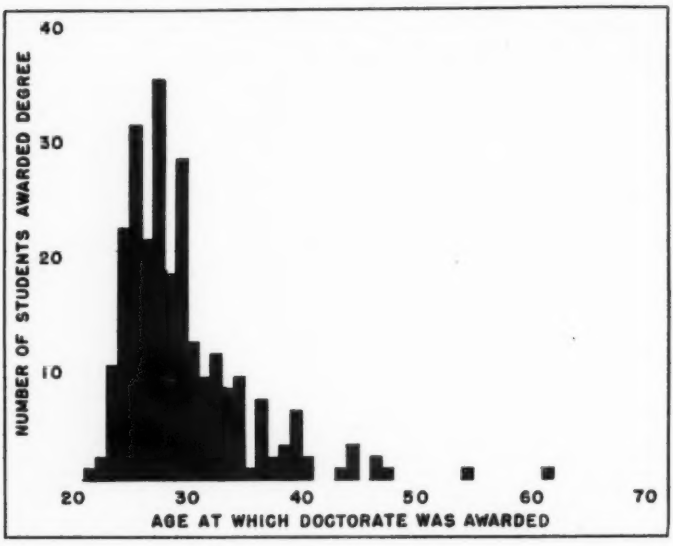
COMPARATIVE LIST OF DOCTORATES IN GEOLOGY GRANTED PRIOR TO 1931 AND DURING THE DECADE 1931–40

School	Prior to 1931	1931–40	Total
Chicago	104	52	156
Yale	91	27	118
Johns Hopkins	88	24	112
Harvard	66	70	136
Columbia	57	38	95
Wisconsin	43	25	68
California	43	30	73
Princeton	40	46	86
Cornell	33	26	59
Stanford	30	16	46
Minnesota	22	32	54
Iowa	20	31	51
Michigan	17	23	40
George Washington	17	3	20
Massachusetts Institute of Technology	16	25	41
Toronto	13	23	36
Pennsylvania	6	2	8
Bryn Mawr	5	3	8
Illinois	5	12	17
Nebraska	5	.....	5
McGill	5	18	23
Indiana	4	6	10
Brown	4	.....	4
Virginia	4	.....	4
California Institute of Technology	3	33	36
Ohio State	3	7	10
Vanderbilt	3	.....	3
New York	3	8	11
American	2	.....	2
Washington (Seattle)	2	2	4
Missouri	2	9	11
Pittsburgh	2	.....	2
North Carolina	2	6	8
Fordham	1	.....	1
Radcliffe	1	2	3
Syracuse	1	.....	1
Cincinnati	1	5	6
Oregon	1	1	2
Colorado	1	9	10
Kansas	1	4	5
Washington and Lee	1	.....	1
Arizona	.....	9	9
Catholic University of America	.....	1	1
Clark	.....	2	2
Colorado School of Mines	.....	12	12
Louisiana State	.....	6	6
Northwestern	.....	6	6
Oklahoma	.....	2	2
Rochester	.....	1	1
Rutgers	.....	1	1
St. Louis	.....	4	4
Southern California	.....	2	2
Texas	.....	3	3
Washington (St. Louis)	.....	1	1

tion of Table 2 shows that eight universities (California, Chicago, Columbia, Harvard, Johns Hopkins, Princeton, Wisconsin, and Yale) have given 59 per cent of all doctorates in geology. Before 1931 these same schools had granted approximately 70 per cent of the total. In the past decade they have granted only about 46 per cent. This apparent loss can be explained by the rapid growth of departments of geology in certain institutions, as, for example, Cali-

TABLE 3

AGE DISTRIBUTION OF DOCTORATES IN GEOLOGY, 1931–40



fornia Institute of Technology, which granted only three doctorates in geology prior to 1931 and 33 between 1931 and 1940.

The University of Chicago still remains first in the total number of doctorates granted in geology, but Harvard University has taken first place in the total number granted during the past decade. In 1936 Harvard awarded fourteen doctorates, the largest number yet given by any one school in a single year (Table 1), although in 1935 the University of Chicago granted twelve doctorates in geology.

Table 3 represents graphically the ages at which doctorates were

obtained during the decade 1931–40. These figures, attained by a consideration of only 37 per cent of the total men involved, are believed to give a reliable index to the general trend. According to the available information, the youngest recipient of the Doctor's degree was twenty-two, the oldest sixty-two, the mean age thirty, the mode twenty-eight. It seems probable that the mode might be accounted for by the large number of students who continued from college into graduate work without an apprenticeship. The award of scholarships and fellowships tends to encourage students to continue their studies immediately on completion of the undergraduate courses.

TABLE 4

REPORTED FIELDS OF SPECIALIZATION FOR 87 PER CENT OF DOCTORATES (1931–40)

Field of Specialization	Number	Percentage
General geology	86	14.7
Historical stratigraphic geology	55	9.4
Paleontology	98	16.8
Mineralogy	22	3.7
Economic geology	115	20.0
Petrology and petrography	63	10.8
Structural geology	77	13.2
Seismology and geophysics	18	3.1
Geomorphology	44	7.5
Miscellaneous	5	0.8
Total	583	100.0

The number of older men who completed work for degrees may be partially accounted for by general business recession and the unemployment of many experienced geologists. As there are no age figures available for previous decades, no general conclusions can be drawn.

Special fields in which degrees have been granted are summarized in Table 4. Obvious difficulties have been encountered in attempting to classify these fields. Overlapping of fields has in many instances led to possible faulty classification. In general, regional studies have been classified as general geology, although they may emphasize stratigraphy, structure, petrography, etc. It is believed, however, that the subject matter as listed gives a broad indication of the major fields of interest and specialization of the graduate students.

Occupations are given for 81 per cent of the total number of doctorates in Table 5. Teaching has attracted the largest group (41 per cent). Many of these may have held teaching positions before com-

TABLE 5

OCCUPATIONS REPORTED BY 33 DEPARTMENTS FOR DOCTORATES (1931–40)

Occupation	Number	Percentage of Total reported
Teaching	225	41.3
Industry		
Oil	99	32.9 (18.2 + 14.7)
Mining	80	
Government service		
U.S. Geological Survey	32	
State geological surveys	28	
Canadian Geological Survey	16	
Soil Conservation Service	4	
National Park Service	3	
Tennessee Valley Authority	2	
U.S. Army engineers	1	17.0
Philippine Geological Survey	1	
Foreign survey	1	
U.S. Land Office	1	
U.S. Securities and Exchange Commission	1	
Reconstruction Finance Corporation	1	
U.S. Army	1	
Research	13	2.4
Museum curatorship	10	1.8
Not competitively engaged	9	1.7
Unemployed	6	1.1
Deceased	6	1.1
Consulting geologists	3	0.6
Total	543	99.9

pleting the requirements for the doctorate. It is significant to note that approximately a third of the total number have entered the field of industry. It is apparent that industry is drawing more and more on highly trained technical men. No longer is industry paying

for apprenticeships. That form of training has been relegated to the graduate schools to whom industry looks for capable and well-trained men.

Those listed as not competitively engaged in geology have been so classified because of ill-health, or, in the case of women, because of marriage. Only one instance has been brought to the attention of the writer where the field of geology has been entirely abandoned. Many of these men are now subject to the Selective Service Act and may be withdrawn from their present occupations. Only a single holder of the doctorate in geology has been reported in the army. By the end of 1941 this number will doubtless be greatly increased.

Little information was obtained concerning the number of men who took the doctorate in the same institution in which they had had all their previous training. Several schools have indicated that they do not permit or encourage this procedure. Others have indicated that it is their policy to urge undergraduates to go elsewhere for a Master's degree and then return for the doctorate.

The large number of doctorates conferred in geology presents a serious problem. It has become increasingly difficult for graduates to obtain employment without advanced degrees, while at the same time it has become increasingly difficult for holders of the doctorate in geology to obtain suitable employment. The large numbers of doctorates and the difficulty of obtaining employment has caused a lowering of the general opinion of the value of the degree. In all probability, with a world at peace, the present decade would have witnessed a general raising of academic requirements and a decrease in the number of degrees conferred. The future is, however, unpredictable on the basis of the past. It is fortunate for the country that we enter the uncertain future with a large supply of well-trained young geologists.

REVIEWS

Principles of Sedimentation. By WILLIAM H. TWENHOFEL. New York: McGraw-Hill Book Co., Inc., 1939. Pp. x+609; figs. 44. $5.00.

This book, prepared as a text for university courses in sedimentation and as a reference work for professional geologists, follows seven years after the second edition of the *Treatise on Sedimentation*, of which Twenhofel was editor and principal author. It is, however, not to be considered as a new edition of the *Treatise*, but rather as a wholly new book. Although somewhat shorter (the *Treatise* had 915 pages), the present work seems to present a better balance than the *Treatise* in the proportion of space assigned to the various subjects. Technically, the book has been carefully edited and proofread, the reviewer having noticed only six typographical errors. The subject lends itself to somewhat more illustrative matter than has been used, but it could not have been more fully illustrated without increasing the size and cost of the volume.

Sedimentation is a large field bordering on and utilizing the results of many branches of geology, notably dynamic geology, geomorphology, paleontology, mineralogy, petrography, and structural and economic geology, and in addition draws extensively from researches in such other branches of science as ecology, oceanography, meteorology, hydraulic engineering, soil science, bacteriology, and organic and inorganic chemistry. To cover the multitude of topics in sedimentation requires a familiarity with an immense quantity of literature and most careful organization and planning. This has been accomplished in the present work, and it may be called a complete, though concise, treatment of the field.

The organization and emphasis are different from those in the *Treatise*. Environments of sedimentation to which quite limited space was allotted at the end of the *Treatise* are considered first, occupying approximately 20 per cent of the volume. This is in accord with growing interest, especially on the part of petroleum geologists, in the environmental conditions of origin of sedimentary formations older than the Recent. After environments, the following topics are considered: origin of inorganic sediments (including weathering), 4 per cent of the volume; interrelations of sediments and organisms, 6 per cent; transportation and deposition of sediments, 13 per cent; the clastic and chemical (including organic) sediments, 40 per cent; sedimentary structures, 13 per cent; and textures and colors, 3 per

cent. Field and laboratory studies of sediments, which were treated briefly in the *Treatise*, have been omitted, as these topics are the subject of the newer volume, *Methods of Study of Sediments*, by Twenhofel and S. A. Tyler (1941).

The subject matter is very concisely and directly presented. The reader is impressed with the great mass of literature upon which the author has drawn as authority for his statements, but, even though the book is fairly large, there seems to be not a paragraph or even a sentence of unnecessary statement. The organization of subject matter is excellent, and as the same pattern of organization is followed for successive topics, such as the various agents of deposition of sediments and the various sedimentary products, it is easy to locate the discussion of a particular topic. Each major division of a chapter is followed by a Bibliography, and there are altogether about six hundred citations of the literature. The author has not intended this Bibliography to be exhaustive but has attempted to include reference to the more important articles since the publication of the second edition of the *Treatise*.

The author believes in the great importance of direct observation of present-day sedimentary processes, products, and structures, considering these a more valuable groundwork for the science than laboratory experiments in which conditions are different from those in nature, or the quantitative measure of certain properties of sediments as a guide to their origin. He is careful to distinguish between what is positively known, what is a logical deduction from known facts, and what is pure speculation. He may be considered conservative in that he does not fully accept an interpretation unless all parts are based on known fact. The following quotation is representative of the caution exercised by the author throughout the book.

"Manganese deposits do not commonly occur in strata that have an abundance of fossils, but before this may be given significance it should be demonstrated whether that means there was a paucity of life on the bottoms."

He questions the value of basal conglomerate as a guide to unconformities and doubts that basal conglomerates are, in fact, as common as most writers have suggested. He believes that chert and flint must have formed in accord with several of the theories by which they have been explained.

The relation of organisms to the environments, processes, and products of sedimentation, and to the structures of sediments, is more fully treated than in previous books, reflecting the author's wide acquaintance with paleontology as well as with sedimentation.

When used as a textbook in a graduate course, the reviewer has found *The Principles of Sedimentation* an excellent summary treatment of the multitude of topics composing this branch of geology. As the statements on each topic are very condensed, the book has been used as an outline and guide to the reading of numerous original articles which give the student a fuller understanding of the various investigations which have led to the results summarized by Twenhofel. Professor Twenhofel has informed the reviewer that he uses the book in much the same way with his graduate classes. The book should provide students wishing to carry on research in sedimentation with a fine summary of important problems awaiting investigation.

HAROLD R. WANLESS

Coal: Its Properties, Analysis, Classification, Geology, Extraction, Uses, and Distribution. By ELWOOD S. MOORE. 2d ed. New York: John Wiley & Sons, Inc., 1940. Pp. ix+473; pls. 20; figs. 151. $6.00.

This work seems but slightly altered from the first edition considering that nearly twenty years have elapsed. The book is reset in somewhat smaller type, with no change in general organization, but an increase of ten pages. There is new material regarding thin sections and the petrographic constituents of coal. Parr's classification is treated in more detail, and the A.S.T.M. classification is given. Under "Origin of Coal" there is some expansion (McKenzie Taylor theory, effects of heat and pressure, bogheads). A page has been added on early plants. The section on "Operation on Public Lands" is re-written. The chapter on the "Mining of Coal" is lengthened. There are other improvements of a more minor nature that serve to bring the book up to date, but the last four chapters are practically unchanged. For instance, under almost any state heading the references given all antedate 1922, in spite of the fact that in most cases much work has been done since then.

Moore's book is a very valuable one and should be in the library of anyone really interested in coal. Its only counterpart in English is the work by Bone and Himus. About two-thirds of the former is devoted to geology, with the remainder split nearly equally between chemistry and engineering. On the other hand, some two-thirds of the latter is given to engineering.

D. J. F.

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